Highway Safety Manual Knowledge Base

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The original document prepared by the NCHRP 17-27 project team included a review of studies that were published until December 2004. This updated version includes accident modification factors (AMFs) based on a review of studies from January 2005 until April 2008. The update was done by the following individuals based on funding from the Federal Highway Administration:

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Preface

The Knowledge Base forms the foundation for the contents of each chapter of Part D of the First Edition of the Highway Safety Manual (HSM). It is expected that this Knowledge Base, which documents the extensive literature review completed, will be of interest to highway safety professionals, and will be of use for the development of future editions of the HSM.

The following chapters are included in this document:

- Chapter 3: Roadway Segments
- Chapter 4: Intersections
- Chapter 5: Interchanges
- Chapter 6: Special Facilities and Geometric Situations
- Chapter 7: Road Networks

In this document, safety effects are presented as Accident Modification Factors or Functions (AMFs). AMFs are typically estimated for three accident severities: fatal, injury, and non-injury. Fatal and injury are generally combined and noted as injury. Where distinct AMFs are available for fatal and injury severities, they are presented separately. Non-injury severity is also known as property-damage-only severity.

Each AMF is accompanied by a measure of accuracy, the standard error. A small standard error indicates that an AMF is accurate. The development of the Knowledge Base of the Highway Safety Manual (HSM) required a formalized process and procedure to review, document, and filter the multitude of safety information published in the last 50 years until April 2008. The procedures that were applied in the development of the Knowledge Base including the method correction factors (MCFs) are provided in a companion document: “Inclusion Process and Literature Review Procedure for Part D”

Chapter 3: Roadway Segments

Chapter 3. Roadway Segments

CONTENTS

EXHIBITS

EQUATIONS

3.1. Safety Effects of Roadway Segment Design Elements

The following sections provide information on the safety effect of design elements on roadway segments. Design components are organized by cross-section elements, roadside elements, and alignment elements.

3.1.1. Roadway Elements

The following sections contain information on the safety effects of:

1. Lanes
2. Shoulders
3. Medians

3.1.1.1. Lanes

In the past, wider lanes have been assumed to be beneficial to safety for two reasons. First, wider lanes should increase the average separation between vehicles in adjacent lanes. This may provide a wider buffer to absorb any deviation of vehicles from their intended path. However, drivers adapt to the road they see. Wider lanes tend to induce somewhat faster travel speeds (as evident in the relationship between lane width and free flow speed (*1*), pg 20-5) and may induce closer following. Whether this complex adaptation to wider lanes increases or decreases safety cannot be determined using intuition or engineering judgment.

Second, wider lanes may provide more room for driver correction in near-accident circumstances. For example, on a roadway with narrow lanes, a moment's inattention may lead a vehicle over the pavement edge-drop and onto a gravel shoulder, but if the lane is wider and the shoulder paved, the same inattention will provide greater opportunity to maintain the vehicle on the paved surface. In these near-accident circumstances, it will be difficult to separate between the effect of lane width, shoulder width, shoulder paving, edge-drops, etc.

It is likely that lane width plays a somewhat different role in single and multi-lane roads. The lane width requirements for single-lane roads were originally derived from the observation of driver behavior. The lane width at which drivers did not feel the need to shift to the right when meeting an oncoming truck was deemed appropriate. The same criterion may apply to the inner lane of an undivided multi-lane lane road, but it may not apply to the other lanes or to divided roads. [Adapted from Hauer, 2000 (*2*).]

Bicycle lane considerations are discussed in Section 3.3, and Chapter 6 provides information on work zone design including lanes.

Exhibit 3-1: Resources examined to investigate the safety effect of lane attributes on road segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., Srinivasan, R., Baek, J., Persaud, B., Lyon, C., Council, F.M., Eccles, K., Lefler, N., Gross, F., Hauer, E., and Bonneson, J., "Crash Reduction Factors for Traffic Engineering and ITS Improvements." NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including increasing lane width and four to three lane conversions (i.e., Road Diets).	Modified lane width and road diet AMF.
(Lord, D., and Bonneson, J.A., "Development of Accident Modification Factors for Rural Frontage Road Segments in Texas." Transportation Research Board 86th Annual Meeting, Washington D.C., (2007))	Developed AMF values for lane width along rural frontage roads in Texas.	AMF added to synthesis
(*3*) (Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Used four years of HSIS crash, traffic and inventory data for urban undivided four-lane roadways in Washington State to develop cross-sectional models of safety.	Added to synthesis (multi-lane lane width).
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies to reduce crashes on horizontal curves.	No additional information; not added to synthesis.
(*4*) (Bauer, K. M., Harwood, D. W., Hughes, W. E., and Richard, K. R., "Safety Effects of Using Narrow Lanes and Shoulder-Use Lanes to Increase the Capacity of Urban Freeways." Washington, D.C., 83rd Transportation Research Board Annual Meeting, (2004))	Used HSIS data to examine 50 miles of a variety of projects on California urban freeways. Applied empirical-Bayes before/after methodology.	AMFs added to synthesis.
(Harwood, D. W., "Methodology to Predict the Safety Performance of Urban and Suburban Arterials." NCHRP Project 17-26 Interim Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2004))	Literature review is included in this report, including some discussion of past work on lanes.	No new knowledge. Not added to synthesis.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of lane width based on findings of three studies	All studies used were pre-1985 studies. Not added to synthesis.
(*5*) (Harwood, D. W., Rabbani, E. R., Richard, K. R., McGee, H. W., and Gittings, G. L., "NCHRP Report 486: Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Study of the effects of roadway factors on safety in 3R projects	Added to synthesis (multi-lane lane width).

DOCUMENT	DESCRIPTION	COMMENT
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Several strategies to reduce run-off-road crashes.	No additional information; not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Several strategies to reduce head-on crashes.	No additional information; not added to synthesis.
(Wooldridge, M. D., Fitzpatrick, K., Harwood, D. W., Potts, I. B., Elefteriadou, L., and Torbic, D. J., "NCHRP Report 502: Geometric Design Consistency on High-Speed Rural Two-Lane Roadways." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Study complements work done for IHSDM; focus is on geometric design consistency of two-lane rural roads.	Same AMFs for lane width as Harwood et al. (2000) used in IHSDM. Not added to synthesis.
(*6*) (Huang, H. F., Stewart, J. R., and Zegeer, C. V., "Evaluation of Lane Reduction "Road Diet" Measures on Crashes and Injuries." Transportation Research Record, No. 1784, Washington, D.C., Transportation Research Board, National Research Council, (2002) pp. 80-90.)	Examined 11 road diet sites and 25 similar comparison sites in six California and two Washington cities	Added to synthesis.
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Investigated statistical relationship between crashes and roadway design attributes on the Oregon state highway system; developed crash models (freeway v. non-freeway) (urban v. non-urban).	Not added to synthesis, questions regarding model form and parameters.
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Research on rural two-lane highways for Part III of the HSM addressed the relationship between lane width and safety.	Added to synthesis. Suggested by NHCRP 17-18(4).
(*2*) (Hauer, E., "Lane Width and Safety." (2000))	Detailed review of literature on lane width from the 1950's through 1999, mostly two-lane rural.	Added to synthesis. Suggested by NHCRP 17-18(4).
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Review of past literature, two-lane roads only.	No additional information; not added to synthesis.
(Council, F. M. and Stewart, J. R., "Safety effects of the conversion of rural two-lane to four-lane roadways based on cross-sectional models." Transportation Research Record, No. 1665, Washington, D.C., Transportation Research Board, National Research Council, (1999) pp. 35-43.)	Developed models to predict crashes/km-year for typical four-lane divided and undivided roads using HSIS data from four states	As reviewed by Hauer 2000 (multi-lane lane width). Surface width was not found to be a significant predictor for 4-lane undivided roads. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Gibreel, G. M, Easa, S. M, Hassan, Y., and El-Dimeery, I. A., "State of the Art Review of Highway Geometric Design Consistency." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1999) pp. 305-313.)	Literature review of highway geometric design consistency, primarily on two-lane rural highways. Discussion of speed, safety, and performance.	Limited quantitative safety effect information on lanes; from older studies (1973-1975). Not added to synthesis.
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Analysis of several roadside characteristics on about 100 km of State Route 3 in Washington State using negative binomial models.	Due to uncertainty of lane elements in models, not added to synthesis.
(Stewart, D. and Council, F. M., "To smooth or not to smooth, that is the question. An analysis of accidents on rural NC two-lane and four-lane roads." (1998))	Examined the safety effects of conversion from two-lanes to four-lanes using cross-sectional models	As reviewed by Hauer 2000 (multi-lane lane width). Lane width was not part of final models. Not added to synthesis.
(Wang, J., Hughes, W. E., and Stewart, R., "Safety effects of cross-section design on rural multi-lane highways." FHWA-RD-98-071, McLean, Va., Federal Highway Administration, (1998))	Developed negative-binomial and Poisson models for non-freeway multi-lane roads	As reviewed by Hauer 2000 (multi-lane lane width). Lane width was not part of final models. Not added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Limited information on improvements.	No quantitative information; not added to synthesis.
(Curren, J. E., "NCHRP Report 369: Use of Shoulders and Narrow Lanes to Increase Freeway Capacity." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Analyzed crash data to determine the effect on safety of using shoulders with or without narrows lanes to increase freeway capacity; safety evaluation was conducted on five corridors	Suggested by NHCRP 17-18(4). As reviewed by Hauer 2000. Not added to synthesis.
(Hadi, M. A., Aruldhas, J., Chow, L., and Wattleworth, J., "Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression." Transportation Research Record 1500, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 169-177.)	Analyzed FL crash data to estimate the effect of cross-section design elements (including lane width) on the safety of urban highways	Suggested by NHCRP 17-18(4). As reviewed by Hauer 2000 (multi-lane lane width). Not added to synthesis.
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	Discussion of safety effect of various cross-section elements.	No additional information; not added to synthesis.
(McCoy, T. A., McCoy, P. T., Haden, R. J., and Singh, V. A., "Safety Evaluation of Converting On-Street Parking from Parallel to Angle." Transportation Research Record 1327, Washington, D.C., Transportation Research Board, National Research Council, (1991) pp. 36-41.)	Studied removal of lanes to provide on-street angle parking in CBD of Lincoln, Nebraska.	Not added to synthesis.
(Harwood, D. W., "NCHRP Report 330: Effective Utilization of Street Width on Urban Arterials." Washington, D.C., Transportation Research Board, National Research Council, (1990))	Evaluated the safety effect of reallocating urban arterial street width to create more lanes; 35 improvement projects	Suggested by NHCRP 17-18(4). As reviewed by Hauer 2000. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V., Reinfurt, D. W., Hummer, J., Herf, L., and Hunter, W., "Safety Effects of Cross-Section Design for Two-Lane Roads." Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 20-32.)	Cross-sectional analysis of data from seven states to study the effects of various roadway parameters including lane width.	As reviewed by Hauer 2000 (two-lane lane width). Not added to synthesis.
(Urbanik, T. and Bonilla, C. R., "Safety and Operational Evaluation of Shoulders on Urban Freeways." FHWA/TX-87/32+395-1, Austin, Tex., Texas State Department of Highways and Public Transportation, (1986))	Summarizes past studies	Suggested by NHCRP 17-18(4). No new research on lanes. Not added to synthesis.
(Harwood, D. W., "NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways." Washington, D.C., Transportation Research Board, National Research Council, (1986))	Cross-sectional models for suburban multi-lane roadways	As reviewed by Hauer 2000 (multi-lane lane width). Lane width not a statistically significant predictor; not added to synthesis.
(Glennon, J. C., "Accident Effects of Centerline Markings on Low-Volume Rural Roads." Transportation Research Record 1027, Washington, D.C., Transportation Research Board, National Research Council, (1985) pp. 7-13.)	Comparison of low-volume rural roads that were either unmarked, marked with dashed centerline, or marked with both dashed centerline and no-passing zone stripes.	More relevant to pavement marking discussion. Not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis of various studies for several traffic control and roadway elements.	No additional knowledge, not added to synthesis.
(McCasland, W. R., "Modifying Freeway Geometrics to Increase Capacity." Transportation Engineering Journal, Vol. 106, No. 6, New York, N.Y., American Society of Civil Engineers, (1980) pp. 787-801.)	Summarizes safety experiences, from past projects from various states that increased lanes by reducing shoulder width	Suggested by NHCRP 17-18(4). Hauer's review indicated simple comparison of accident rates. Not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Review of the safety effect of cross-sectional elements.	No additional information, not added to synthesis.

Treatment: Widen lanes

Rural two-lane roads

Hauer (2000) (*2*) conducted a detailed review of literature on lane width from the 1950s through 1999. Hauer also reanalyzed some of the data using improved research methods than available when the original studies were completed. Hauer's review is felt to be the best of many syntheses and reviews conducted. Hauer concluded (*2*):

1. A great deal of empirical evidence has been accumulated over several decades. The bulk of it pertains to two-lane rural roads. Little is known about the effect of lane width on multi-lane roads or urban roads.

2. When road sections differ in lane width they tend to differ also in other important respects. This makes the isolation of the safety effect of lane width difficult.
3. In spite of this difficulty, there is a great deal of congruence between the results. Thus, the AMFs obtained by Belmont (1954), Cope (1955), Roy Jorgensen (1978), Zegeer et al. (1987) and Miaou (1996) are very similar when brought to the common denominator of ‘all accidents’.
4. There is, however, one issue on which opinions differ. Most early researchers found that the safety benefit of lane widening bottoms out somewhere between 11 ft and 12 ft. Further widening seemed to be to the detriment of safety. Later researchers, using perhaps better data and methods of analysis, unfortunately choose to use in their models a functional form that can never reach a ‘bottom’. Nor is there any evidence in their work that before choosing this functional form they examined whether their data indicated an increase in crashes for wider lanes. For this reason, in Hauer’s opinion, the weight of the extant empirical evidence indicates that there is little safety benefit to be obtained from widening lanes beyond 11 ft and that widening beyond 12 ft may be to the detriment of safety (on two-lane roads).
5. There is some empirical evidence about the safety effect of reducing lane width on urban arterials and freeways when the aim is to add a lane to increase capacity. This evidence is difficult to interpret in terms of the safety effect of lane width because when a lane is added (even when no other changes are made) the flow/lane is significantly changed.

Unfortunately, even though Hauer’s third conclusion notes similar findings for “all accidents” from several studies, an AMF was not specified for any changes in lane parameters. The following summary of studies is based on Hauer’s synthesis.

Belmont (1954) analyzed data that pertains to rural two-lane tangents, without structures or intersections, predominantly straight and level and with a 55 mph posted speed limit (*2*). Using Poisson regression, Hauer reanalyzed the data and developed the following AMFs:

Pavement Width (in ft)	18	20	22	24	26	28	30
AMF	1.21	1.05	1.00	1.01	1.06	1.13	1.21

Standard deviations were not reported for these estimates, and could not be calculated based on available knowledge. In addition, since the original data included some paved shoulders, it is not possible to simply assume that dividing these pavement widths in half will provide lane widths.

Cope (1955) analyzed before/after data for 22 pavement widening projects (*2*). Most of the projects involved widening from 18 to 22 ft. Accidents that occurred at driveways, intersections, and entrances were extracted. Hauer notes that the large accident reductions found in the analysis were partially due to regression-to-mean (RTM), since the mean “before” accident rates were higher than the state average, and because a greater reduction was seen for the projects with higher “before” period rates (*2*). Hauer omitted some of the projects with the most obvious RTM biases and estimated an AMF of 0.7 for widening from 18 to 22 ft; an approximate 8% crash reduction per foot of pavement widening up to 22 ft. This is higher than seen in the Belmont figures noted above (perhaps because all RTM was not removed, and because the “total” accidents here are actually a smaller subset; the driveway crashes were deleted). Using 22 ft as the "base", the AMFs are estimated to be:

Pavement Width (in ft)	18	20	22	24	26	28	30
AMF	1.43	1.16	1.00	?	?	?	?

Standard deviations were not reported for these estimates, and could not be calculated based on available knowledge.

Hauer notes that Roy Jorgensen Associates (1978) originally attempted an elaborated linear regression modeling effort using data from Maryland, New York and Washington (*2*). When the linear modeling did not produce satisfactory results, a multiplicative model was used to produce accident modification factors. Hauer further notes that even though the authors noted a consistent increase in accident rate between lane widths of 21 to 22 ft and pavement widths of 23 ft and greater, they merged these two cells ("…for conservatism in estimating the geometric effects on safety") (*2*). Hauer and other authors believe this result to be questionable, and Hauer presents the unadjusted AMFs from their work as:

Pavement Width (in ft)	18 or less	19-20	21-22	>23
AMF	1.25	1.10	1.00	1.11

Standard deviations were not reported for these estimates, and could not be calculated based on available knowledge.

Zegeer et al. (1987) conducted a cross-sectional analysis of data from seven states to study the effects of various roadway parameters including lane width (*2*). Hauer notes that the form of the function for lane width in the resulting model forced the effect to be the same per foot of lane width increase, regardless of the initial lane width. Thus, the form did not allow an increase in the AMFs for the wider lane widths as was seen in the studies above. (Subsequent conversations with the authors indicated that forms other than those in the final paper were used, and that the 12 ft lanes did indeed exhibit a slightly lower crash rate.) Hauer also noted that Zegeer's finding of an 11% reduction in total crashes per foot of lane width increase could have been the result of lane width, curvature and driveway frequency, since these latter two variables are correlated with lane width and thus dropped from the final model (*2*). If the 11% reduction is correct, using 22 ft pavement width as the base again, the following values would result. Once more, standard deviations were not reported for these estimates, and could not be calculated based on available knowledge.

Pavement Width (in ft)	18	20	22	24	26	28	30
AMF	1.26	1.12	1.00	0.89	?	?	?

Miaou (1996a) analyzed data from two-lane rural roads in Alabama, Michigan, and Washington (*2*). Hauer does not document the type of analysis conducted, but it is assumed that this was a cross section (regression) study. The form of the model used was not described. Miaou finds a 14% reduction in single-vehicle run-off-road crashes for each foot of lane width increase (*2*). Converting this finding to reduction in total crashes requires an estimate of the percent of total crashes that are single-vehicle run-off-road. If one assumes a figure of 66% (*7*), and assumes no effect of lane width on multi-vehicle crashes, the resulting AMF would be approximately 9% per foot of lane widening (or 18% per 2 ft pavement width widening). The resulting values are shown below. Again, standard deviations were not reported for these estimates, and could not be calculated based on available knowledge.

Pavement Width (in ft)	18	20	22	24	26	28	30
AMF	1.18	1.09	1.00	.92	?	?	?

Miaou (1996b) also reanalyzed a subset of 1,282 pure rural road sections from the original data analyzed by Zegeer et al. in 1987 (*2*). Again, the form of the regression model was not indicated, but it appears that the form did not allow a "bottom" in crashes per mile. Covariates included a dummy variable for State, AADT per lane, lane width, shoulder width, roadside recovery distance, horizontal curvature, terrain type, vertical grade, sideslope, intersections per mile, driveways per mile, bridges per mile, and roadside hazard rating. Hauer notes that the findings indicate an AMF of $e^{-0.078(\text{lane width change in ft.})}$ (*2*).

This would translate into approximately 7.5% reduction in total crashes per foot of increase in lane width. The resulting values are shown below, again using 22 ft as the base value. Standard deviations were not reported for these estimates, and could not be calculated based on available knowledge.

Pavement Width (in ft)	18	20	22	24	26	28	30
AMF	1.17	1.08	1.00	.84	?	?	?

Exhibit 3-2 combines the findings of the above studies, presenting the indices of effectiveness derived from each of the studies for various pavement widths for all crash types and severities.

If one accepts Hauer's and others' judgment of an increase in crash risk for lane widths of over 12 ft, and no difference between 11 and 12 ft lanes, then the first three columns in Exhibit 3-2 are most relevant. If one further hypothesizes that the amount of RTM bias in the results is negligible to some extent (or has been minimized by Hauer's reanalysis in some cases), then, except for the Cope study, the study findings are somewhat consistent. Since standard errors for each study result were not available or calculable, the combined average was calculated as the arithmetic average of the studies, excluding Cope (e.g., for 18 ft, (1.21+1.25+1.26+1.18+1.17) / 5 = 1.21). An estimate of the standard error for the combined average was computed based on Equation 3-1, and then a method correction factor of 3 was applied due to the variations in site characteristics between the studies.

Equation 3-1: Estimate of s ideal for arithmetic average of studies

$$s = \sqrt{\frac{1}{n-1}\left[\sum x_i^2 - \frac{1}{n}\left(\sum x_i\right)^2\right]}$$

where n = sample size (in this case 5 studies)

x_i = index of effectiveness of study i

Exhibit 3-2: Individual and combined AMFs for lane width for all crash types on two-lane rural roads as reviewed by (Hauer, 2000) (2)

Study	**Pavement width in feet (Lane width in ft)**			
	18 (9)	**20 (10)**	**22 (11)**	**24 (12)**
Belmont	1.21	1.05	1.00	1.01
Cope	*1.43*	*1.16*	*1.00*	*?*
Jorgenson	1.25	1.10	1.00	1.11
Zegeer	1.26	1.12	1.00	0.89
Miaou(a)	1.18	1.09	1.00	0.92
Miaou(b)	1.17	1.08	1.00	0.84
Average of all studies excl. Cope	**1.21**	**1.09**	**1.00**	**0.95**
S ideal	0.040	0.026	0	0.107
MCF	3	3	3	3
S	**0.121**	**0.078**	**0.000**	**0.321**

As part of the development of the accident prediction module for FHWA's Interactive Highway Safety Design Model (IHSDM), a panel of experts used a combination of the Hauer review and their personal knowledge to define the AMFs for lane width on two-lane rural roads (*7*).

As noted in Exhibit 3-3, the AMFs provided are for selected crash types (i.e., single-vehicle run-off-road, multiple-vehicle same-direction sideswipe, and multiple-vehicle opposite-direction). However, a conversion equation was provided by Harwood et al. to convert these to AMFs for total crashes (*7*). Using that equation, and converting the findings for AADT of 2,000 veh/day and above to an 11 ft lane width base of 1.0 to correspond with the earlier findings, the following AMFs are derived (Exhibit 3-4).

Exhibit 3-3: AMFs for lane width for selected crash types on two-lane rural roads (7)

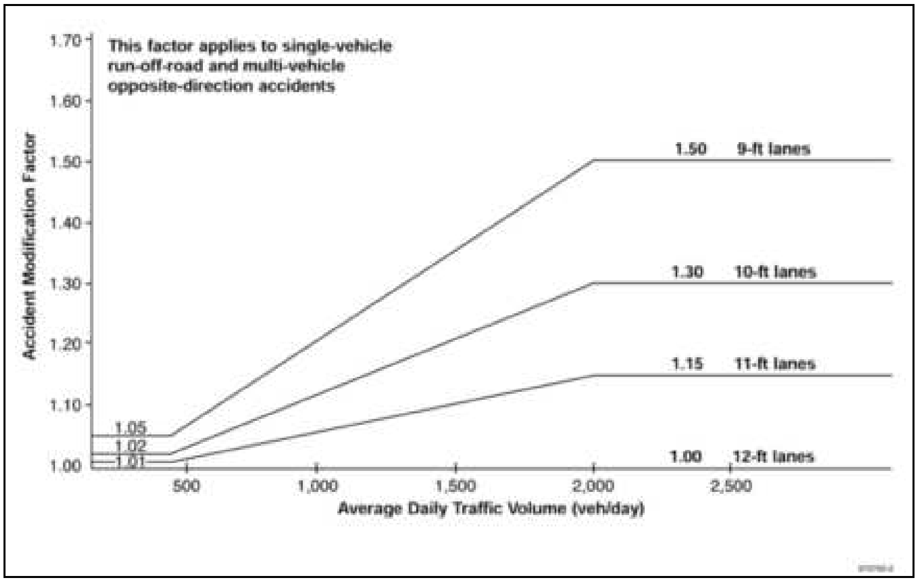


Exhibit 3-4: AMFs for lane width on two-lane rural roads with AADT of 2,000 veh/day or more (7)

	Pavement width (ft) [Lane width (Ft)]			
	18 [9]	**20 [10]**	**22 [11]**	**24 [12]**
Selected crash types	1.42	1.23	1.00	0.95
Total crashes	1.15	1.08	1.00	0.98

It is noted that the results for total crashes here are similar to, but slightly lower than, the AMFs derived for 9 ft and 10 ft lanes in Exhibit 3-2. In all probability, the values in Exhibit 3-3 and Exhibit 3-4 are used more often than any others, since these values are incorporated into IHSDM, the draft prototype chapter of the HSM, and other current references such as the NCHRP Report 500 series. Exhibit 3-3 provides an AMF for different AADT levels; therefore, it is suggested that the AMFs used in the IHSDM also be used in the HSM (i.e., Exhibit 3-3 and Exhibit 3-4). However, it is noted that the crash reductions shown for a conversion from 11 to 12 ft lanes is questionable. In lieu of further research, the solution is to rely on the AMFs developed for Chapter 8 of the HSM (Exhibit 3-3).

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Hauer (2000) noted in his review of literature up to 1999 that, "Little is known about the effect of lane width on multi-lane roads or urban roads" (*2*). Hauer reviewed five studies of lane and surface width on multi-lane roads: Harwood, 1986; Hadi et al., 1995; Stewart and Council, 1998; Wang et al., 1998; and Stewart and Council, 1999. None of the studies provided sufficient quantification of the safety effect of lane width on multi-lane highways, freeways, or arterials (*2*). Only the Hadi et al. study included lane width as a variable in models developed; the following summary is based on Hauer's review.

Hadi et al. (1995) developed negative binomial cross-sectional models predicting safety for nine classes of roadway. (*2*) While both lane width and pavement width were examined for inclusion in the final multi-lane models, lane width was only found to be a statistically significant predictor in three of the seven multi-lane models, and pavement width was not found to be a statistically significant predictor in any of the four models where it was analyzed. Hauer noted that this only meant that these variables were not statistically important enough for inclusion in the models (*2*). Where statistical significance was reached, findings would indicate an 11% reduction in crashes per foot of lane width on four-lane undivided roads, and over 35% reduction in crashes per foot of lane width for urban freeways. Hauer notes that these latter findings are clearly excessive, and that the form of the model forced lane width to have a continuing effect no matter how wide the lane (i.e., 12 ft lanes would be forced to be safer than 11 ft lanes, 13 ft safer than 12 ft, etc.), a conclusion Hauer questions (*2*).

Elvik and Vaa's (2004) meta-analysis of lane width used the findings from three studies (*8*). All were pre-1985 studies, and the one U.S. study used was reviewed by Hauer, but not considered a "key" study. Elvik and Vaa did not search for safety effects by lane width; rather, they reviewed the studies' findings based on changes from less than "design standards" to a width meeting standards. In their summary, Elvik and Vaa indicate that the findings were "inconsistent". No information was added to this synthesis of knowledge.

*In a recent study of the effects of roadway factors on safety in 3R projects, Harwood et al. (2003) reviewed in detail past AMFs (*5*). For lane width, the authors used the AMFs from Harwood et al. (2000) (7) which were developed for two-lane rural roads. For multi-lane roads, the original AMFs were subjected to a correction factor for total crashes for each roadway type. For 4-lane undivided roads, the correction factor applied was 0.75. For 4-lane divided roads, the correction factor was 0.5. While there is no information in the report concerning how these correction factors were developed, consultation with the author indicated that an expert panel developed the correction factors. Using these factors to adjust the total accident AMFs in Exhibit 3-4, the following AMFs for total crashes on four-lane roads are developed (*
Exhibit 3-5). As illustrated in Harkey et al. (2008), the AMF values for the effect of lane width on rural multilane highways are calculated using Equation 3-2 (168):

Equation 3-2: Lane width AMF estimate for rural multilane highways

$$AMF = f\,(AMF_{RA} - 1.0)P_{RA} + 1.0$$

where

f = factor for roadway type (0.75 for multilane undivided and 0.50 for divided)

AMF_{RA} = accident modification factor for related accidents (as determined for rural two-lane roads)

P_{RA} = proportion of total accidents constituted by related accidents

Harkey et al. (2008) note there is less confidence in the rural multilane AMF than the AMF for rural two-lane roads.

Exhibit 3-5: AMFs for lane width for four-lane roads (5)

	Lane width (ft)			
	9	**10**	**11**	**12**
Four-lane undivided	1.11	1.06	1.00	0.99
Four-lane divided	1.08	1.04	1.00	0.99

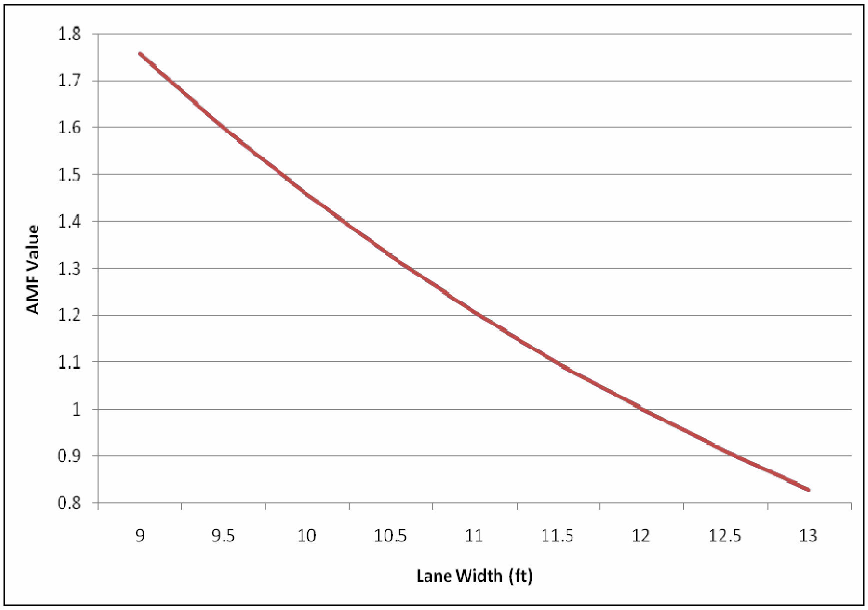
Hauer et al. (2004) used four years of HSIS crash, traffic and inventory data for urban undivided four-lane roadways in Washington State to develop cross-sectional models of safety (*3*). In addition to the standard roadway cross-section (e.g., lane and shoulder width) and alignment (e.g., horizontal curvature and grade), supplemental databases and videolog reviews were used to add data on such items as roadside clear zone and roadside hazard rating, driveway and access point counts, the presence of parking, and two-lane-left-turn lanes. Since lane width was not in the original data, it was developed from surface width and number of lanes, with a parking width correction (where parking was allowed). The range was 10 ft to 12 ft. Negative multinomial models were developed separately for off-road and on-road crashes. The choice of which predictor variables to include in the final model and the choice of the *functional form of each predictor* were based on an analysis of the predictor's relationship to crashes given previously included parameters – an iterative process not seen in other modeling efforts. Lane width was not found to be related to off-road crashes on these urban undivided four-lane roads. In the on-road accident model, the authors noted a very weak relationship between lane width and safety, with crashes increasing approximately 1.5% per foot as lane width increased from 10 to 12 ft (*3*).

In summary, there is little evidence in the literature that lane width affects crash rate per mile on multi-lane roads. All of the findings are derived from cross-sectional studies, where lane width effects could possibly be masked by correlation with other predictors. The only definitive AMFs stated in the literature are those from Harwood et al. (
Exhibit 3-5), which are based on expert-panel modification of rural two-lane road AMFs (which were based on an earlier expert panels' review of literature). At this time, this is the best available knowledge for the HSM.

Rural frontage roads

Lord and Bonneson (2007) developed AMFs for rural frontage roads using Texas data (*169*). Lord and Bonneson investigated rural frontage roads independent of typical two-lane roads because they have restricted access along at least one side of the road, a higher percentage of turning traffic, and periodic ramp-frontage-road terminals with yield control. Due to these differences, a given treatment likely has a different effect on rural frontage road safety than on rural two-lane road safety. Exhibit 3-6 illustrates the AMFs for lane width on rural frontage roads between successive interchanges.

Exhibit 3-6: Safety Effects of Lane Width for Rural Frontage Roads (169)



The average lane width represents the total width of the traveled way divided by the number of through lanes on the frontage road. Relative to 12-ft lanes, 9-ft wide lanes increase the number or accidents more than either 10-ft or 11-ft lanes.

Both one-way and two-way frontage roads were considered in the development of this AMF. Development of this AMF was limited to lane widths ranging from 9 to 13 ft and ADT values from 110 to 6,168 veh/day.

In summary, the research by Lord and Bonneson (2007) presents the only definitive AMFs for lane width on rural frontage roads. At this time, this is the best available knowledge for the HSM.

Treatment: Add lanes in existing ROW by narrowing existing lanes and shoulders

Rural two-lane roads

Not applicable.

Rural multi-lane highways; Freeways; Expressways

Hauer's review of Curren (1995) reveals some information of the safety effect of adding lanes in an existing right-of-way by narrowing the existing lanes and shoulders (*2*). Curren (1995) examined the safety effects of adding freeway lanes by narrowing lanes and shoulders, comparing approximately 50 miles of "altered" interstate corridors in four states with 35 miles of "unaltered" sections on the same route. Citing problems with the original analysis methodology, Hauer reanalyzed the one route where a before/after with comparison group analysis could be conducted. Hauer found that accident rate per mile increased by 68% on suburban freeways, and increased by 26% on urban freeways (*2*). Insufficient information was reported to determine a standard error for these increases.

In the most recent study of defining new lanes from existing pavement width, Bauer et al. (2004) used HSIS data to examine 50 miles of projects on California urban freeways (*4*). Projects involved conversion from either four lanes to five in one direction or from five lanes to six lanes in one direction. In almost all cases, the added lane was an HOV lane for at least part of each day. While the lane and shoulder widths differed among the projects, the majority involved narrowing lanes from 12 ft to 11 ft, with inside shoulders narrowed to capture the needed additional width for the extra lane. All treatment, reference, and upstream and downstream control roadways had median barriers in both the before and after periods.

Using the empirical-Bayes before-after methodology, Bauer et al. found that the four- to five-lane conversions, on the average, resulted in a statistically significant average increase in total accident frequency of 11% (*4*). The five-lane to six-lane conversion projects resulted in an average increase in total accident frequency of 3%, which was not statistically significant. The standard errors reported by Bauer et al. for the average changes to accident frequency were multiplied by a factor of 1.8 (medium-high rating); the resulting values are presented in Exhibit 3-7.

Bauer et al. also found possible "accident migration" to adjacent downstream sites (where the extra lane no longer existed) to be a non-statistically significant crash increase for the four-lane to five-lane conversions of 1% to 9%, and a statistically significant increase of 17% to 21% downstream from the five-lane to six-lane conversions (Exhibit 3-7) (*4*). An effect that potentially offsets the accident migration on the five-lane to six-lane conversions was a non-significant decrease in crash frequencies for freeway segments upstream of the conversion site (where the added lane may have relieved congestion and queuing). Bauer et al. note that because of the differences in the findings for the two types of projects, the results obtained are difficult to generalize to urban freeways as a whole (*4*).

Exhibit 3-7: AMFs for providing an additional lane on urban freeways by narrowing 12 ft lanes to 11 ft or wider and narrowing the inside shoulder (4)

Author, date	**Treatment / Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**	**Possible accident migration**
Bauer et al, 2004	Four to five lane conversion	Urban	Freeway, 79,000 to 128,000 vpd, one direction	All types, all severities	1.11	0.05	0.80% (not statistically significant)
Bauer et al, 2004	Four to five lane conversion	Urban	Freeway, 79,000 to 128,000 vpd, one direction	All types; fatal, injury and PDO tow-away	1.10	0.07	7.56% (not statistically significant)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s	Possible accident migration
Bauer et al, 2004	Four to five lane conversion	Urban	Freeway, 79,000 to 128,000 vpd, one direction	All types, fatal and injury	1.11	0.08	8.81% (not statistically significant)
Bauer et al, 2004	Five to six lane conversion	Urban	Freeway, 77,000 to 126,000 vpd, one direction	All types, all severities	1.03	0.08	18.11% (statistically significant)
Bauer et al, 2004	Five to six lane conversion	Urban	Freeway, 77,000 to 126,000 vpd, one direction	All types; fatal, injury and PDO tow-away	1.04	0.11	17.33% (statistically significant)
Bauer et al, 2004	Five to six lane conversion	Urban	Freeway, 77,000 to 126,000 vpd, one direction	All types, fatal and injury	1.07	0.13	21.33% (statistically significant)

In summary, the congestion and delay reductions that result from defining additional lanes within a given surface width may result in an increase in crashes. Given the methodology used in the two available studies, the best estimate of the safety effect for freeways where HOV lanes are added to freeways by reassigning the existing pavement width is based on the Bauer et al. study (Exhibit 3-7).

Urban and suburban arterials

Hauer (2000) concluded that, "There is some empirical evidence about the safety effect of reducing lane width on urban arterials and freeways when the aim is to add a lane to increase capacity. This evidence is difficult to interpret in terms of the safety effect of lane width because when a lane is added (even when no other changes are made) the flow/lane is significantly changed" (*2*). Hauer reviewed Harwood (1990), and the following summary is based on that review.

Harwood (1990) analyzed before-after data for 35 projects on urban arterials where existing lanes were narrowed to add additional lanes. Harwood found large accident increases in the conversion of a two-lane road to an undivided four-lane road, but the crash increases were mainly at driveways and intersections, which reflect other factors (*2*). When a 5-lane (with TWLTL) was converted to 7-lanes (with TWLTL), there was an increase in both mid-block and intersection crash rates. When a 6-lane divided road was converted to 8-lane divided, the crash increase was only at intersections. Hauer noted that it is not possible to separate out the effects of lane width changes from other effects (such as addition of TWLTL or median) (*2*). AMFs could not be developed from this study.

Treatment: "Road diets" (remove through lanes from existing ROW)

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials

"Road diets" are generally conversions of four-lane undivided roads into three lanes (two through plus a center two-way left-turn lane). The remaining roadway may be converted to bicycle lanes, sidewalks, or on-street parking (*6*).

Huang et al. (2002) examined 11 "road diet" sites and 25 similar comparison sites in six California and two Washington cities. Using a paired-comparison before-after method in the examination of crash frequencies, Huang et al. found that, "The estimated risk ratio indicates that the percent of crashes at road diet sites in the "after" period to be about 6% less likely than a crash at a comparison site, with 95% confidence limits of 0.003 and 0.106. Thus, on average, crash frequencies at "road diets" in the "after" period were approximately 6% lower than at the corresponding comparison sites" (*6*). This translates to an index of effectiveness of 0.94. The standard error is based on the 95% confidence limits (divided by 4) provided by Huang et al., multiplied by a method correction factor of 3 (low rating), due to the likely selection of sites for implementing the "road diet" based on high accident counts, resulting in a standard error estimate of 0.078.

A second analysis attempted to correct for possible differences in exposure between the "road diet" treatment and comparisons sites, and between the before and after periods. Huang et al. developed negative-binomial regression models for sites where ADT was available (eight "road diet" sites and 14 comparison sites). This analysis showed no difference in crashes between the before and after periods for the treatment vs. the comparison sites (*6*). Further analysis of crash severity and crash types shows no statistically significant differences due to the "road diet" treatment. Huang et al. concluded that "road diets" appear to decrease total crashes "by six percent or less" (*6*).

Huang et al. were not able to conduct an empirical Bayes (EB) analysis due to data limitations, and the rate-based modeling was on a limited sample.

Harkey et al. (2008) used the data from the Huang et al. (6) study along with additional data collected by Pawlovich et al. (*170*) and conducted an EB analysis of the aggregated data sets. This provided for a large group of sites that spanned a number of roadway environments in which the "road diets" were implemented. Exhibit 3-8 presents the results of the analysis for each data set along with the aggregated results. The sites in Iowa ranged in AADT from 3,718 to 13,908 and were predominantly on US or State routes in small urban towns with an average population of 17,000. The sites in Washington and California ranged in AADT from 6,194 to 26,376 and were predominantly on corridors in suburban environments that surrounded larger cities with an average population of 269,000.

Exhibit 3-8: AMFs for "Road Diets" (168)

Dataset	AMF	Standard error
IA	0.534	0.020

CA and WA	0.811	0.025
All	0.707	0.016

The research by Harkey et al. (2008) is a more definitive study in that it is based on a much larger data set and used an EB analysis approach.

3.1.1.2. Shoulders

The principal purposes of providing shoulders are to:

- Accommodate stopped vehicles so that they do not encroach on the traveled lane
- Facilitate roadway maintenance
- Facilitate access by emergency vehicles
- Protect the structural integrity of the pavement
- Provide space for slower vehicles to move over and allow faster vehicles to pass (in some driving cultures)

The main purposes of paving shoulders are: to protect the physical road structure from water damage, to protect the shoulder from erosion by stray vehicles, and to enhance controllability of stray vehicles. As a by-product of these purposes, the paved shoulder provides a fairly even and obstacle free surface.

While the original intent of shoulders was to provide for vehicles that have to stop (i.e., involuntary or emergency stops), the fully paved shoulder also induces some amount of voluntary stopping. Vehicles stopped on shoulders pose a substantial hazard. It has been estimated that more than 10% of all fatal freeway accidents are associated with stopped-on-shoulder vehicles or with the maneuvers associated with leaving and returning to the outer lane.

Other concerns with providing wider shoulders include:

- The possibility that wider shoulders result in higher operating speeds, which in turn may impact accident severity
- Steeper side or backslopes that may result from wider roadway width and limited right-of-way
- Drivers who may choose to use the wider shoulder as a travel lane

It follows that the net safety effect of shoulders is a sum of several possibly opposite tendencies: the beneficial effect of allowing for the safe recovery of stray vehicles, and the detrimental tendencies of inviting some voluntary shoulder stops, faster travel, the possibility of steeper roadside slopes, and shoulder use for travel.

Several factors make it difficult to extract the safety effect of shoulder width and shoulder paving from empirical evidence. For example, narrow lanes, narrow unpaved shoulders, and an unforgiving roadside often go hand-in-hand. This tendency comes about for three reasons. First, many geometric design standards relate to the amount of traffic. Roads with little traffic tend to have narrower lanes and shoulders, steeper side-slopes, sharper curves, shorter sight-distances, etc. Second, if a cross-section has to fit within a given right-of-way width, making the shoulder wider must mean that the side-slope will be steeper or the lane narrower. The third reason for the close association between road features is temporal. There has been a historical evolution towards more generous highway design standards. Thus, older roads tend to have narrower lanes and shoulders than newly designed roads. *[Adapted from Hauer (2000) (9).]*

This section includes discussion of shoulder width for two-lane and multi-lane roads, and a discussion of the safety effectiveness of various shoulder types. Pedestrians and bicyclists are discussed in detail in Section 3.3.

Exhibit 3-9: Resources examined to investigate the safety effect of shoulder attributes on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., R. Srinivasan, J. Baek, B. Persaud, C. Lyon, F.M. Council, K. Eccles, N. Lefler, F. Gross, E. Hauer, J. Bonneson, "Crash Reduction Factors for Traffic Engineering and ITS Improvements", NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including adding or widening a paved shoulder on rural multilane highways	No new knowledge. Not added to synthesis.
(Lord, D., J.A. Bonneson, "Development of Accident Modification Factors for Rural Frontage Road Segments in Texas", Transportation Research Board 86th Annual Meeting, Washington D.C., (2007))	Developed AMF values for shoulder width along rural frontage roads in Texas.	AMF added to synthesis
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Refers to strategies in ROR Guide, which referred to Harwood, et al., 2000, reviewed above for shoulder width/type AMFs	No new knowledge. Not added to synthesis.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results not available.
(*3*) (Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Developed negative multinomial models relating off- and on-road crashes to design elements on four-lane undivided highways	Added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Referred to Harwood et al., 2000, reviewed above for shoulder width/type AMFs	No new knowledge. Not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Referred to Harwood et al., 2000, reviewed above for shoulder width/type AMFs	No new knowledge. Not added to synthesis.
(Wooldridge, M. D., Fitzpatrick, K., Harwood, D. W., Potts, I. B., Elefteriadou, L., and Torbic, D. J., "NCHRP Report 502: Geometric Design Consistency on High-Speed Rural Two-Lane Roadways." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Study complements work done for IHSDM; focus is on geometric design consistency of two-lane rural roads.	Same AMFs for lane width as Harwood et al. (2000) used in IHSDM. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*5*) (Harwood, D. W., Rabbani, E. R., Richard, K. R., McGee, H. W., and Gittings, G. L., "NCHRP Report 486: Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Reviewed past studies and extracted or defined AMFs for various design elements on multi-lane roads	Added to synthesis, shoulder width and shoulder type.
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Developed AMFs based on NB and ZINB model coefficients for design elements on freeways and non-freeways	Suggested by NCHRP 17-18(4). Not added to synthesis, questions regarding model form and parameters.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Referred to Zegeer (1987) and Harwood (2000) – both reviewed above	No new knowledge. Not added to synthesis.
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Developed SPFs and AMFs for a variety of design elements on two-lane rural segments.	Suggested by NCHRP 17-18(4). Added to synthesis.
(*9*) (Hauer, E., "Shoulder Width, Shoulder Paving and Safety." (2000))	Reviewed AMF and SPF literature on SW and reanalyzed some data sets	Suggested by NCHRP 17-18(4). Evaluation of several studies added to synthesis and expanded.
(Hanley, K. E., Gibby, A. R., and Ferrara, T. C., "Analysis of Accident Reduction Factors on California State Highways." Transportation Research Record, No. 1717, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 37-45.)	Conducted EB before/after analysis of two shoulder widening projects	Not added to synthesis. Small sample size, result is much higher than all other studies.
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Developed AMFs for ROR crashes based on NB and ZINB model coefficients related to design elements of two-lane rural highway	Not added to synthesis due to uncertainty in modeling methodology.
(Gibreel, G. M, Easa, S. M, Hassan, Y., and El-Dimeery, I. A., "State of the Art Review of Highway Geometric Design Consistency." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1999) pp. 305-313.)	Literature review of highway geometric design consistency, primarily on two-lane rural highways. Discussion of speed, safety, and performance.	No quantitative safety effect information on shoulders. Not added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Limited information on improvements.	No quantitative information; not added to synthesis.
(Curren, J. E., "NCHRP Report 369: Use of Shoulders and Narrow Lanes to Increase Freeway Capacity." Washington, D.C., Transportation Research Board, National Research Council, (1995))	As reviewed by Hauer, 2000.	No new knowledge. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*10*) (Hadi, M. A., Aruldhas, J., Chow, L., and Wattleworth, J., "Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression." Transportation Research Record 1500, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 169-177.)	Developed NB cross-sectional models for various design elements on different road classes	Suggested by NCHRP 17-18(4). As reviewed by Hauer 2000 (two-lane, and multi-lane), added to synthesis.
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	As reviewed by Hauer, 2000.	No new knowledge. Not added to synthesis.
(*11*) (Zegeer, C. V., Reinfurt, D. W., Hummer, J., Herf, L., and Hunter, W., "Safety Effects of Cross-Section Design for Two-Lane Roads." Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 20-32.)	Developed cross-sectional models and AMFs for various design elements on two-lane roads	As reviewed by Hauer 2000 (two-lane shoulder width and shoulder type), added to synthesis.
(Urbanik, T. and Bonilla, C. R., "Safety and Operational Evaluation of Shoulders on Urban Freeways." FHWA/TX-87/32+395-1, Austin, Tex., Texas State Department of Highways and Public Transportation, (1986))	As reviewed by Hauer, 2000.	No new knowledge. Not added to synthesis.
(*12*) (Harwood, D. W., "NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways." Washington, D.C., Transportation Research Board, National Research Council, (1986))	Cross-sectional model of various design elements on multi-lane suburban roads	Suggested by NCHRP 17-18(4). As reviewed by Hauer 2000 (multi-lane). Added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis of past studies.	No new knowledge. Not added to synthesis.
(*13*) (Rogness, R. O., Fambro, D. B., and Turner, D. S., "Before-After Accident Analysis for Two Shoulder Upgrading Alternatives." Transportation Research Record 855, Washington, D.C., Transportation Research Board, National Research Council, (1982) pp. 41-47.)	Developed AMFs for adding paved shoulders to two-lane rural roads based on a simple before/after analysis	Reviewed for shoulder type, added to synthesis.
(*14*) (Heimbach, C. L., Hunter, W. W., and Chao, G. C., "Paved Highway Shoulders and Accident Experience." Transportation Engineering Journal, Vol. 4, New York, N.Y., American Society of Civil Engineers, (1974) pp. 889-905.)	Developed AMF for paving 3-4 ft. of existing sod shoulders on two-lane rural roads, based on comparison of match sites.	Reviewed for shoulder type, added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Synthesis of past studies.	No new knowledge. Not added to synthesis.

Treatment: Increase shoulder width

Rural two-lane roads

Hauer (2000) conducted a detailed review of 1953 to 1999 literature on shoulder width and type, sometimes reanalyzing the data in the study (Exhibit 3-10) (*9*). The majority of the studies concerned two-lane rural roads. Unfortunately, Hauer did not highlight any studies as "excellent" and had methodological and other issues with all of the studies reviewed. Hauer notes that the study results were "diverse and confusing", with the following conclusions (*9*):

- Several studies point to the fact that shoulder width is more beneficial to safety at higher traffic volumes than at lower ones;
- There is an indication that roads with wider shoulders tend to have more severe accidents;
- There is an indication that wider shoulders are associated with fewer run-off-road and opposite-direction accidents that are some 40%-60% of all accidents (on two-lane roads). However, wider shoulders may be associated with more of the 'other' accidents;
- It is possible that for injury accidents, there is a certain shoulder width (perhaps between 6 and 8 ft) beyond which the number of injury accidents increases;
- The safety effect of shoulders for level and straight roads is probably substantially less than on sharp horizontal curves and on roads with substantive grades;
- Roads with paved shoulders are associated with fewer accidents than similar roads with sod shoulders;
- Provision of full shoulders instead of only curb-and-gutter on multi-lane suburban highways is associated with a 10% lower accident rate.

Hauer did not draw any conclusion concerning the size of the effect of increasing the shoulder width. "Critical" studies identified by Hauer are included in Exhibit 3-10 (i.e., no "major" methodological problems were noted, or the data were reanalyzed). In addition, the focus for this synthesis of knowledge is on studies where intersection crashes were omitted and studies with results related to changes in total crashes. Finally, only U.S. studies were included in Exhibit 3-10, since the use of paved shoulders in non-U.S. countries may differ from the U.S. (e.g., use of shoulder to allow passing in non-U.S. countries). Standard errors could not be calculated for the indices of effectiveness summarized in Exhibit 3-10.

Exhibit 3-10: Summary of study characteristics for shoulder width on two-lane rural roads

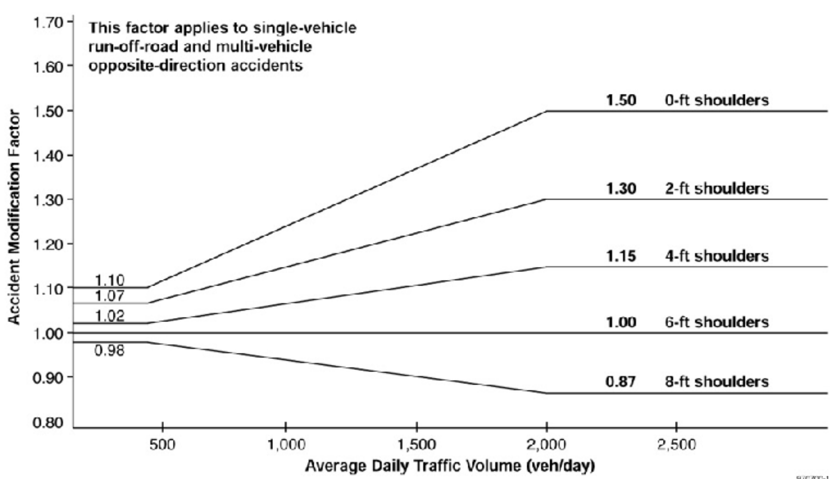
Author, date	**Treatment/ Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Belmont, 1954 (Hauer re-analysis) (*9*)	Widen gravel shoulders by 1 ft	Rural	Two-lane, volumes not reported	All types, all severities	1.0	Unable to calculate.
Belmont 1956 (Hauer Re-analysis) (*9*)	Widen gravel shoulders by 1 ft	Rural	Two-lane, volumes not reported	All types, all severities	1.0	Unable to calculate.
Head and Kaestner, 1956 (*9*)	Widen gravel shoulders by 1 ft	Rural	Two-lane, AADT < 3600	All types, all severities	0.98	Unable to calculate.
Head and Kaestner, 1956 (*9*)	Widen gravel shoulders by 1 ft	Rural	Two-lane, AADT > 3600	All types, all severities	0.95 to 0.89	Unable to calculate.
Zegeer et al., 1987 (*11*)	Widen shoulders by 1 ft	Not reported	Two-lane, volumes not reported	All types, all severities (includes	0.95 to 0.94	Unable to calculate.

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
				intersection crashes)		
Hadi et al., 1995 (*10*)	Widen shoulders by 1 ft	Rural	Two-lane, volumes not reported	All types, all severities	0.985	Unable to calculate.
Miaou, 1996 (*9*)	Widen shoulders by 1 ft	Rural	Two-lane, volumes not reported	All types, all severities	0.970	Unable to calculate.
Vogt and Bared, 1998 (*9*)	Widen shoulders by 1 ft	Rural	Two-lane, volumes not reported	All types, all severities	0.944	Unable to calculate.

Only one study reviewed by Hauer (Head and Kaestner, 1956) examined the effect of widening gravel shoulders. Although a positive safety effect is indicated by the results of that study (based on Hauer's reanalysis), AMFs could not be developed for gravel shoulder widening.

As part of the development of the accident prediction module for FHWA's Interactive Highway Safety Design Model (IHSDM), a panel of experts used the Hauer review and their knowledge to define the AMFs for shoulder width on two-lane rural roads (*7*). The results were based primarily on Zegeer et al. (1987) and Miaou (1996) (Exhibit 3-11).

Exhibit 3-11: AMFs for shoulder width for related accidents on two-lane rural roads (7)



Note that the results in Exhibit 3-11 are for "related accidents" (i.e., single-vehicle run-off-road and multi-vehicle opposite-direction accidents) rather than total accidents. As can be seen, there is an AADT effect. Hauer argues that there may be adverse effects on "non-related accidents". However, assuming no adverse effect, these "related-accident" effects were extrapolated to effects on total crashes as prescribed by Harwood et al. (*7*). The total-crash effects were then converted such that the crash reductions were based on a 3 ft shoulder "base" rather than the 6 ft base shown in the figure. The results are presented in Exhibit 3-12.

Exhibit 3-12: AMFs for total crashes on two-lane rural roads with ADT of 2,500 veh/day or greater (7)

Study	**Paved shoulder width in ft (on one side)**					
	3	**4**	**5**	**6**	**7**	**8**
Harwood et al., 2000 (total crashes)	1.0	0.97	0.95	0.93	0.91	0.90

The indices of effectiveness for paved shoulder width in Exhibit 3-13 are related to total accidents. It is noted that the minimum and maximum shoulder widths were not always mentioned in the reviewed studies. Despite this fact, in Exhibit 3-13, it is assumed that the effects noted in the studies apply at least to the 3 ft to 8 ft widths. Taking the arithmetic average of the study results, and using Equation 3-1 in conjunction with a method correction factor of 3 (low rating), the results of the various studies reviewed by Hauer and the results from Harwood et al. were combined.

Exhibit 3-13: Summary of AMFs for paved shoulder widening on total crashes on two-lane rural roads with any volume

Study	**Paved Shoulder width in ft (on one side)**					
	3	**4**	**5**	**6**	**7**	**8**
Belmont, 1954 (Hauer re-analysis)	1.0	1.0	1.0	1.0	1.0	1.0
Belmont 1956 (Hauer Re-analysis)	1.0	1.0	1.0	1.0	1.0	1.0
Zegeer et al., 1987	1.0	0.95	0.90	0.85	0.80	0.75
Hadi et al. 1995	1.0	0.98	0.97	0.96	0.94	0.92
Miaou, 1996	1.0	0.97	0.94	0.91	0.89	0.86
Vogt and Bared, 1998	1.0	0.94	0.89	0.84	0.79	0.74
Harwood et al. 2000 (ADT ≥ 2500 veh/day)	1.0	0.97	0.95	0.93	0.91	0.90
Combined AMF	**1.00**	**0.97**	**0.95**	**0.93**	**0.90**	**0.88**
S	**0.000**	**0.069**	**0.132**	**0.196**	**0.256**	**0.319**

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Hauer (2000) conducted a detailed review of 1953 to 1999 literature on shoulder width and type, sometimes reanalyzing the data in the study (*9*). The results of three studies that examined shoulder width on multi-lane roads are summarized in Exhibit 3-14.

Exhibit 3-14: Summary of study characteristics for shoulder width on multi-lane roads (9)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood, et al. 1986 (*12*)	Full paved shoulders instead of curb-and-gutter	Suburban	Multi-lane roads, ADT>7500	All crashes, all severities	0.90	Unable to calculate.
Hadi et al., 1995	Widen shoulders by 1 ft	Rural	Four-lane divided, volumes not reported	All crashes, all severities	Shoulder width not statistically significant	Unable to calculate.
Hadi et al., 1995	Widen shoulders by 1 ft	Urban	Four-lane undivided, volumes not reported	All crashes, all severities	0.97	Unable to calculate.

In a recent study of the effects of roadway factors on safety in 3R projects, Harwood et al. (2003) reviewed in detail past AMFs (*5*). For shoulder width, the authors used the AMFs from Harwood et al. (2000). The report did not include a correction factor to convert the AMF for total crashes on two-lane roads to multi-lane roads (Exhibit 3-15). Communications with the author and review of an internal progress report indicated that the expert panel concluded that the effects of shoulder width on rural multi-lane roads should be the same as on two-lane roads. Thus, under the same assumptions stated above related to the conversion of effects on related crashes versus total crashes, the shoulder width effect for multi-lane roads would be assumed to be the same as for two-lane roads. Insufficient information was available to calculate standard errors for these values.

Exhibit 3-15: AMFs for total crashes on urban or rural multi-lane roads with ADT of 2,500 veh/day or greater (5)

Study	Paved shoulder width in ft (on One side)					
	3	4	5	6	7	8
Harwood et al., 2003 (total crashes)	1.0	0.97	0.95	0.93	0.91	0.90

Hauer et al. (2004) used four years of HSIS crash, traffic and inventory data for urban undivided four-lane roadways in Washington State to develop negative multinomial cross-sectional models of safety (*3*). In addition to the standard roadway cross-section (e.g., lane and shoulder width) and alignment (e.g., horizontal curvature and grade), supplemental databases and videolog reviews were used to add data on such items as roadside clear zone and roadside hazard rating, driveway and access point counts, the presence of parking, and two-way-left-turn lanes.

The choice of which predictor variables to include in the final model and the choice of the functional form of each predictor were based on an analysis of the predictor's relationship to crashes given previous parameters had already been included – an iterative process not seen in other modeling efforts. Hauer et al. categorized shoulders as either curb/wall, or flush of widths 2 to 3 ft, 4 to 6 ft, 7 to 9 ft, 10 to 11 ft, and over 11 ft. The shoulder-width findings for flush shoulders were counter-intuitive, in that the wider the shoulder, the more crashes for both off-road and on-road crashes. Total off-road crashes increased approximately 15% per 2 ft increase in flush shoulder width, while on-road crashes increased by approximately 4% per 2 ft increase (*3*). Hauer notes that it is difficult to determine whether these findings are true cause and effect, or the result of common modeling issues such as imprecise functional form and correlation with other variables.

Exhibit 3-16: AMFs for crashes on urban or rural multi-lane roads (3)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hauer et al., 2004	Widen shoulders by 1 ft	Urban	Four-lane undivided, volume not reported	Off-road crashes, all severities	1.07	Unable to calculate.
Hauer et al., 2004	Widen shoulders by 1 ft	Urban	Four-lane undivided, volume not reported	On-road crashes, all severities	1.03	Unable to calculate.
Hauer et al., 2004	Widen shoulders by 1 ft	Urban	Four-lane undivided, volume not reported	All crashes, all severities (Assume off-road crashes = 15% of total)	1.03	Unable to calculate.

As part of NCHRP Project 17-25, an expert panel was convened and considered the effect of shoulder width on rural multilane highways and urban/suburban multilane arterials (*168*). The expert panel reached consensus that the shoulder width AMF for rural multilane highways developed by Harwood et al. (2003) was an acceptable AMF for this roadway type. For the other roadway types, the effect of shoulder width on multi-lane roads is not yet fully established. It appears that there is a general safety benefit when providing wider shoulders. The opposite appears to be the case for urban road segments.

Rural frontage roads

Lord and Bonneson (2007) developed AMFs for rural frontage roads in Texas. It was determined to investigate rural frontage roads independent of typical two-lane roads because rural frontage roads have restricted access along at least one side of the road, a higher percentage of turning traffic, and periodic ramp-frontage-road terminals with yield control (*169*). Due to these differences, a given treatment likely has a different effect on rural frontage road safety than on rural two-lane road safety.

Equation 3-3 presents the AMF for shoulder width on rural frontage roads between successive interchanges (*169*). Exhibit 3-17 is based on Equation 3-3.

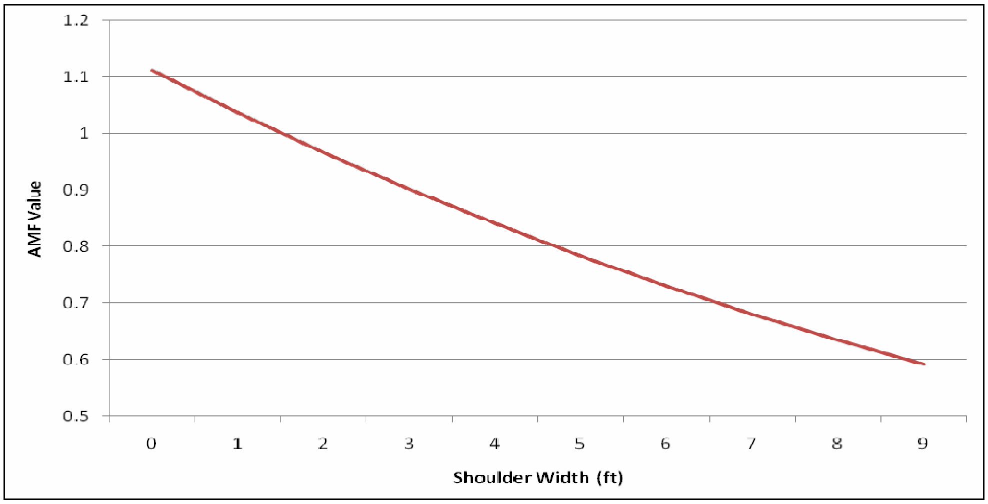
Equation 3-3: Shoulder width AMF estimate for rural multilane highways

$$AMF_{SW}=e^{-0.070(SW-1.5)} \quad (3\text{-}1B)$$

where:

SW = average paved shoulder width ([left shoulder width + right shoulder width]/2) (ft)

Exhibit 3-17*: Safety Effects of Paved Shoulder Width on Rural Frontage Roads (169)*



The average paved shoulder width represents the sum of the left shoulder width and the right shoulder width on the frontage road divided by two. Both one-way and two-way frontage roads were considered in the development of this AMF. Development of this AMF was limited to shoulder widths ranging from 0 to 9 ft and ADT values from 110 to 6,168 veh/day.

Treatment: Improve shoulder type (paved vs. unpaved)

Rural two-lane roads

Hauer (2000) conducted a detailed review of 1953 to 1999 literature on shoulder width and type, sometimes reanalyzing the data in the study (Exhibit 3-18) (*9*). Standard deviations were provided by Hauer for the Heimbach et al. results; the standard deviation was multiplied by a method correction factor of 3 (a medium-low rating for cross-section studies) to estimate the standard error. Standard errors could not be determined for the other studies.

Exhibit 3-18 also includes the results of the Harwood et al. (2000) study, which is the basis for the shoulder type AMFs in FHWA's Interactive Highway Safety Design Model (IHSDM) (*7*). Harwood et al.'s results are based on expert panel findings, and are primarily based on Zegeer et al. (1987) and Miaou (1996) (Exhibit 3-18). While the original tabular results in Harwood et al. were referenced as "related crashes" (i.e., single-vehicle run-off-road and multi-vehicle opposite-direction accidents); assuming no adverse effects, the related crash effects were extrapolated to effects on total crashes as prescribed by Harwood (Exhibit 3-18).

Exhibit 3-18: Summary of study characteristics for shoulder type (7,9)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Heimbach et al., 1974 (*14*)	Pave a 3 to 4 ft sod shoulder	Rural	Two-lane, volumes not reported	All crashes, fatal	0.86	0.57
Heimbach et al., 1974 (*14*)	Pave a 3 to 4 ft sod shoulder	Rural	Two-lane, volumes not reported	All crashes, injury	0.86	0.18
Heimbach et al., 1974 (*14*)	Pave a 3 to 4 ft sod shoulder	Rural	Two-lane, volumes not reported	All crashes, PDO	0.78	0.12
Heimbach et al., 1974 (*14*)	Pave a 3 to 4 ft sod shoulder	Rural	Two-lane, volumes not reported	All crashes, all severities	0.81	0.09
Rogness, 1982 (*13*)	Pave a "full shoulder"	Rural	Two-lane, volumes not reported	All crashes, all severities	0.815	Unable to calculate.
Zegeer et al., 1987	Pave shoulder (per 1 ft)	Rural	Two-lane, volumes not reported	All crashes, all severities (includes intersections)	0.98	Unable to calculate.
Harwood, et al, 2000	Change paved shoulder to turf	Rural	Two-lane, volumes not reported	All crashes, all severities	1.01	Unable to calculate.

Exhibit 3-19 provides AMFs for different shoulder widths and shoulder types also from the Harwood et al. (2000) publication. The base condition for shoulder types is assumed to be a paved shoulder (*7*).

Exhibit 3-19: Accident Modification Factors for Shoulder Types on Two-Lane Highways for single-vehicle run-off-the-road and opposite-direction accidents (7)

Shoulder type	Shoulder width (ft)							
	0	1	2	3	4	6	8	10
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.01	1.01	1.01	1.02	1.02	1.03
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06	1.07
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11	1.14

Note: The values for composite shoulders in this table represent a shoulder for which 50 percent of the shoulder width is paved and 50 percent of the shoulder width is turf.

As can be seen in Exhibit 3-19, gravel shoulders appear to be very similar to paved shoulders. Turf shoulders increase total crashes by approximately one percent on 3 ft shoulders and fourteen percent on 8 ft shoulders.

Standard errors for the AMFs summarized in Exhibit 3-20 could not be determined from the literature. These AMFs provide estimates of effect for converting turf shoulders to paved or composite, or gravel shoulders to paved.

Exhibit 3-20: AMFs for total crashes for conversion to/from different shoulder types on two-lane rural roads

	Shoulder width in ft (on one side)					
Treatment	**3**	**4**	**5**	**6**	**7**	**8**
Convert turf to paved	0.99	0.98	0.97	0.97	0.97	0.96
Convert gravel to paved	1.00	1.00	1.00	0.99	0.99	0.99
Convert turf to composite (partially paved)	1.00	0.99	0.98	0.97	0.98	0.98

Note: The values for composite shoulders in this table represent a shoulder for which 50 percent of the shoulder width is paved and 50 percent of the shoulder width is turf.

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Harwood et al. (2003) is the only study found to provide an AMF for shoulder type on multi-lane roads (*5*). An expert panel reviewed the results of the Harwood et al. (2000) study for two-lane rural roads and concluded that the same AMFs were appropriate for both divided and undivided multi-lane roads. As part of NCHRP Project 17-25, another expert panel was convened and considered the effect of shoulder type on rural multilane highways and urban/suburban multilane arterials (*168*). The expert panel reached consensus that the shoulder type AMF for rural multilane highways developed by Harwood et al. (2003) was an acceptable AMF for this roadway type.

3.1.1.3. Medians

The principal purposes of providing medians are to:

- Separate opposing traffic streams;
- Provide a recovery area for out-of-control vehicles;
- Provide a place where vehicles can stop in emergencies;
- Allow for the accommodation of left-turn lanes and openings for left or U-turn maneuvers;
- Reduce oncoming-vehicle headlight glare (median barrier); and,
- Serve as a reserve for additional future travel lanes.

The design of a median requires several decisions, including:

1. Whether to provide a median (i.e., whether the roadway is to be divided or undivided);
2. How wide the median should be;
3. The shape of the median – flush, depressed or raised;
4. Whether to include a median barrier; and

5. How to design median crossovers.

[Adapted from Hauer (2000) (15).]

This section includes discussion of the three main elements: median presence, median width, and median shape. The safety effects of two-way left turn lanes (a type of "median") are covered in Chapter 6. Other cross-sectional elements of highway medians are discussed in other sections of Chapter 3, including:

- Median geometry, sideslopes, ditches, culverts, other features, and barriers (Section 3.1.2);
- Median refuge islands for pedestrians (Section 3.3); and,
- Median crossovers for access points (Section 3.4.2).

Exhibit 3-21: Resources examined to investigate the safety effect of medians on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., R. Srinivasan, J. Baek, B. Persaud, C. Lyon, F.M. Council, K. Eccles, N. Lefler, F. Gross, E. Hauer, J. Bonneson, "Crash Reduction Factors for Traffic Engineering and ITS Improvements", NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including changing the width of an existing median along rural and urban multilane highways	AMFs added to synthesis
NCHRP Project 17-14, FY 1996 http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-14	Improved Guidelines for Median Safety.	Suggested by NHCRP 17-18(4). Not published as of Mar 8/05.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of 16 median presence studies (1968-1997) Review of two studies on median width. No meta-analysis conducted	Added to synthesis (median presence).
Donnel, T. Eric.; and Masson, Jr. M. John. Predicting the Severity of Median-Related Crashes in Pennsylvania by Using Logistic Regression. Transportation Research Record 1897, TRB, National Research Council, Washington, D.C., 2004, pp. 55-63.	The purpose of the paper was to highlight the probability (odds) of having a fatal, injury or PDO collisions when one or more of the 13 explanatory variables is present.	The safety effect of barriers was not estimated in this study. Not added to synthesis.
(Chayanan, S., Nebergall, M., Shankar, V., Juvva, N., and Ouyang, Y., "Interaction Between the Roadway and Roadside - An Econometric Analysis of Design and Environmental Factors Affecting Segment Accident Rates." WA-RD 562.1, Seattle, Washington State Transportation Center, University of Washington, (2003))	Examination of two different cross-sectional model forms based on 500 1-mile randomly selected sections of WA highways.	Limited review, no AMFs for median variable produced. Not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Literature review and several strategies to reduce head-on crashes on two-lane rural roads.	No relevant information. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*16*) (Neuman,T.R., Pfefer,R., Slack,K.L., Hardy,K.K., Council,F.M., McGee,H., Prothe,L., Eccles,K.A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions" Washington, D.C., Transportation Research Board, National Research Council, (2003))	Literature review and several strategies to reduce run-off-road crashes on two-lane rural roads.	Limited qualitative information added to synthesis.
Donnel,T. E.; Harwood, W. D.; Bauer, M. K.; Mason, M. H. Jr.; and Pietrucha, T. Martin. Cross-Median Collisions on Pennsylvania Interstates and Expressways. Transportation Research Record 1784, TRB, National Research Council, Washington, D.C., 1993, pp. 91-99.	This paper examined the safety issues with cross-median collisions on Pennsylvania Interstates and Expressways. This paper didn't set out to develop or estimate the safety effects of treatments used to counter cross-median collisions. Rather the paper aim to quantify collision frequency based on 3 types of median.	Not added to synthesis
(*17*) (Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Developed AMFs based on NB and ZINB model coefficients for design elements on freeways and non-freeways	While there are questions regarding model form and parameters, added to synthesis (median presence).
(Hunter, W. W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M., and Harkey, D. L., "Three-Strand Cable Median Barrier in North Carolina: In-Service Evaluation." Transportation Research Record, No. 1743, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 97-103.)	Used crash data to evaluate the effect of the installation of cable median barrier on crash rates in NC; only used Interstate locations	No relevant information. Not added to synthesis.
(*15*) (Hauer, E., "The Median and Safety." (2000))	Reviewed AMF and SPF literature on median presence, width, and shape and reanalyzed some data sets	Suggested by NHCRP 17-18(4). No conclusions on AMFs, evaluation of several studies added to synthesis (median presence, median width, median shape) and expanded.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Review of past literature, two-lane roads only.	Not relevant to medians on multi-lane roads. Not added to synthesis.
(*18*) (Council, F. M. and Stewart, J. R., "Safety effects of the conversion of rural two-lane to four-lane roadways based on cross-sectional models." Transportation Research Record, No. 1665, Washington, D.C., Transportation Research Board, National Research Council, (1999) pp. 35-43.)	Cross-sectional models for "typical sections" of three road classes	As reviewed by Hauer, 2000, added to synthesis (median presence).
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Developed AMFs for ROR crashes based on NB and ZINB model coefficients related to design elements of 96 km of one state route	Not added to synthesis due to uncertainty in modeling methodology.

DOCUMENT	DESCRIPTION	COMMENT
(Castronovo, S., Dorothy, P. W., and Maleck, T. L., "An Investigation of the Effectiveness of Boulevard Roadways." Washington, D.C., 77th Transportation Research Board Annual Meeting, (1998))	Used boulevards in Michigan to compare the crash rate of roadway with continuous center left-turn lanes to boulevards	Suggested by NHCRP 17-18(4). Not relevant as this section does not cover TWLTLs. Not added to synthesis.
(*19*) (Nystrom, K., "Median Barrier Study Warrant Review." TE-97-02, Sacramento, California Department of Transportation, (1997))	Developed cross-sectional models built on findings and data from Seamons and Smith 1991 with additional years and examination of more than just cross-median crashes	As reviewed by Hauer, 2000. Hauer's reanalysis results added to synthesis (median width).
(*20*) (Miaou, S. P., "Measuring the Goodness of Fit of Accident Prediction Models." FHWA-RD-96-040, McLean, Va., Federal Highway Administration, (1996))	Developed multivariate model of effect of sideslope on single-vehicle crashes on two-lane undivided roads.	As reviewed by Hauer, 2000, added to median shape synthesis
(Elvik, R., "The Safety Value of Guardrails and Crash Cushions: A Meta-Analysis Of Evidence From Evaluation Studies." Accident Analysis and Prevention, Vol. 27, No. 4, Oxford, N.Y., Pergamon Press, (1995) pp. 523-536.)	Meta-analysis of 32 studies that evaluated the safety effect of median barriers (and guardrails and impact attenuators)	Suggested by NHCRP 17-18(4). No relevant information; barriers are not included in this section. Not added to synthesis.
(*10*) (Hadi, M. A., Aruldhas, J., Chow, L., and Wattleworth, J., "Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression." Transportation Research Record 1500, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 169-177.)	Analyzed FL crash data to develop NB cross-sectional models for various design elements on different road classes	Suggested by NHCRP 17-18(4). As reviewed by Hauer 2000 (two-lane, and multi-lane), added to synthesis (median width).
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Study of the operational and safety considerations of median widths at 40 rural and suburban divided highway intersections	No AMFs. Not added to synthesis.
(Bowman, B. L. and Vecellio, R. L., "Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety." Transportation Research Record 1445, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 169-179.)	Evaluated the safety effect of various medians on vehicular and pedestrian safety; analyzed over 30,000 crashes; 3 cities	Suggested by NHCRP 17-18(4). Included in meta-analysis by Elvik and Vaa (2004). Not added to synthesis.
(Long, G., Gan, C., and Morrison, B. S., "Safety Impacts of Selected Median and Access Design Features." Gainesville, Transportation Research Center, University of Florida, (1993))	Cross-sectional evaluation of effect of median on crashes on urban arterials; various types of medians, no medians, restrictive medians; 400 miles of urban roads in FL	Suggested by NHCRP 17-18(4). Reviewed by Hauer (2000). Simple comparison of raw crash rates without control for other variables; not added to synthesis.
(*21*) (Knuiman, M. W., Council, F. M., and Reinfurt, D. W., "Association of median width and highway accident rates." Transportation Research Record 1401, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 70-82.)	Developed log-linear multivariate cross-sectional models (assuming NB variance function) of *accident rate/mvm* on divided freeways and non-freeways	Reviewed by Council and by Hauer (2000), added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	Overview of impact on safety of various cross-section elements.	No additional information on medians; relevant studies reviewed by Hauer (2000); not added to synthesis.
(*22*) (Seamons, L. L. and Smith, R. N., "Past and Current Median Barrier Practice in California." TE-90-2, Sacramento, Calif., CalTrans, (1991))	Developed cross-sectional models of cross-median crash rates on freeways.	As reviewed by Hauer 2000, Hauer's reanalysis added to synthesis (median width).
(Harwood, D. W., "NCHRP Report 330: Effective Utilization of Street Width on Urban Arterials." Washington, D.C., Transportation Research Board, National Research Council, (1990))	Evaluated the safety effect of reallocating urban arterial street width to create more lanes; 35 improvement projects	No relevant information. Not added to synthesis.
(*12*) (Harwood, D. W., "NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways." Washington, D.C., Transportation Research Board, National Research Council, (1986))	Developed cross-sectional models for various design alternatives on suburban highways	As reviewed by Hauer, 2000, added to synthesis (median presence). Included in meta-analysis by Elvik and Vaa (2004)
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Summary of safety research of various traffic control and cross-section elements.	No additional quantitative information; relevant studies reviewed by Hauer (2000); not added to synthesis.
(*23*) (Foody, T. J. and Culp, T. B., "A comparison of the safety potential of the raised versus depressed median design." Transportation Research Record 514, Washington, D.C., Transportation Research Board, National Research Council, (1974) pp. 1-14.)	Examined total and fatal crash rates per MVM on raised and depressed medians of 84-ft width on Interstate roadway.	As reviewed by Hauer, 2000, added to synthesis (median shape)
(*24*) (Garner, G. R. and Deen, R. C., "Elements of Median Design in Relation to Accident Occurrence." Highway Research Record 432, Highway Research Board, (1973) pp. 1-11.)	Examined accident rates for various medians types and widths on Interstate and turnpike roads in Kentucky	As reviewed by Hauer, 2000. added to synthesis (median shape)
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reviews highway safety aspects of cross-section elements.	No additional quantitative information; relevant studies reviewed by Hauer (2000); not added to synthesis.

Target crashes for median treatments are head-on, opposite-direction sideswipe, and run-off-road-left, generalized as median-related crashes in the following discussion.

Treatment: Provide a median

Rural (and urban) two-lane roads

Elvik and Vaa provide estimates of the safety effect of constructing “central reservations” on the basis of 9 international and 7 U.S. studies (*8*) (pg 326). Although uncommon in North America, Elvik and Vaa found that on rural two-lane roads, medians increase the number of all accident types, both injury and PDO, possibly due to the hindrance of overtaking maneuvers, and the presence of a new hazard (i.e., the median is generally raised or a barrier) (*8*). On two-lane roads in urban areas, Elvik and Vaa found that medians reduced injury accidents of all types by about 40%. This effect is likely related to the restriction of turning maneuvers at minor intersections and accesses (*8*).

Elvik and Vaa's findings are summarized in Exhibit 3-22; the standard error of the safety effect estimates are based on the 95% confidence interval reported by Elvik and Vaa, multiplied by a factor of 1.8, representing a medium-high rating for the meta-analysis.

Exhibit 3-22: Summary of study characteristics for median presence on two-lane roads

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Provide a median	Rural	Two-lane, volume not reported	All types, fatal and injury	1.94	0.558
Elvik and Vaa, 2004	Provide a median	Rural	Two-lane, volume not reported	All types, PDO	2.28	0.549
Elvik and Vaa, 2004	Provide a median	Urban	Two-lane, volume not reported	All types, fatal and injury	0.61	0.099

Rural multi-lane highways; Urban and suburban arterials

Hauer (2000) conducted a detailed review of 1953 to 1999 literature on median presence, and reanalyzed data in some cases (*15*). Hauer did not draw overall conclusions from the studies he reviewed. Exhibit 3-23 includes two of the six studies reviewed by Hauer (2000) that were methodologically sound (Harwood, 1986; Council and Stewart, 1999), a meta-analysis by Elvik and Vaa (2004), and a more recent study by Strathman et al. (2001).

Harwood (1986) found that non-intersection accident rates (per MVM) were approximately 43% higher on divided than undivided suburban residential roads, and approximately 2% higher on suburban commercial roads (*12*). (When total crashes were examined, Harwood found very little difference between the crash rates for divided vs. undivided suburban roads of either type). Although the results of the Harwood (1986) study were included in the meta-analysis by Elvik and Vaa (2004), the results are documented here to provide some knowledge of the suburban setting. This single study of suburban roads would indicate an AMF for median presence of 1.0 for total crashes on both commercial and residential roads and for non-intersection crashes on commercial roads (i.e., no effect), and an AMF of 1.40 for non-intersection crashes on suburban residential roads.

Elvik and Vaa (*8*) (pg 327) present findings for median presence on multi-lane roads for injury and non-injury crashes separately. Elvik and Vaa's findings for rural roads with a median indicate a decrease in crashes of 12% for injury and 18% for PDO crashes. The urban road findings indicate a decrease in crashes for injury (22%) but an increase in PDO crashes (9%). The standard errors presented in Exhibit 3-23 for Elvik and Vaa's findings are based on the 95% confidence intervals reported by the authors, multiplied by a method correction factor of 1.8, as the results of the meta-analysis methodology are deemed to be of medium-high quality.

Using negative binomial and zero-inflated negative binomial models, Strathman, et al. (2001) (*17*) examined the effects of various roadway variables on crashes on Oregon roadways.

Separate models were developed for urban vs. rural, and freeway vs. non-freeway, but not for different road classes (e.g., two-lane vs. multi-lane) within the non-freeway group. It was not possible to determine how the functional form of each variable was derived, or how parameters were excluded from the model (if at all). The models included dummy variables for the presence of vegetative medians, curbed medians, and medians with barriers. While difficult to interpret, the findings appear to indicate that the presence of a vegetative median reduces crashes by approximately 57% on rural non-freeways (regardless of median width). A standard error could not be computed for this value.

Exhibit 3-23: Summary of study characteristics for median presence

Author, date	**Treatment/ Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, t** adjusted	**Estimate of Std. Error, s**
Harwood, 1986 Included in meta-analysis by Elvik and Vaa (2004)	Add median	Suburban (California and Michigan)	Commercial roads, lanes and volume not reported	Non-intersection, all severities	1.02	Unable to calculate.
Harwood, 1986 Included in meta-analysis by Elvik and Vaa (2004)	Add median	Suburban (California and Michigan)	Residential roads, lanes and volume not reported	Non-intersection, all severities	1.43	Unable to calculate.
Council and Stewart, 1999 (*18*)	Add median	Rural (California)	Four-lane, volume not reported	Non-intersection, all severities	$= 0.76 \times ADT^{-0.05}$	Unable to calculate.
Elvik and Vaa, 2004	Add median	Urban	Multi-lane, volume not reported, includes minor intersections	All types, injury	0.78	0.018
Elvik and Vaa, 2004	Add median	Urban	Multi-lane, volume not reported, includes minor intersections	All types, PDO	1.09	0.018
Elvik and Vaa, 2004	Add median	Rural	Multi-lane, volume not reported, includes minor intersections	All types, injury	0.88	0.0315
Elvik and Vaa, 2004	Add median	Rural	Multi-lane, volume not reported, includes minor intersections	All types, PDO	0.82	0.0315
Strathman et al. 2001	Vegetative medians	Rural	Non-freeways, volumes not reported	Non-intersection, all severities	0.43	Unable to calculate.

The results of the four studies that provided AMFs are distinct. Three of the studies examined non-intersection crashes (Harwood, Council and Stewart, and Strathman), and Elvik examined total crashes (intersection and non-intersection combined) by severity class.

Findings from the studies of rural roads by Council and Stewart, and Strathman et al. are somewhat consistent with each other, but disagree significantly in both degree and direction from the Harwood findings for suburban roads.

The single study of suburban roads would indicate an index of effectiveness for median presence of 1.02 for total crashes on both commercial and residential roads and for non-intersection crashes on commercial roads (i.e., no effect), and an index of effectiveness of 1.43 for non-intersection crashes on suburban residential roads. Standard errors could not be calculated for these values.

Freeways; Expressways

No studies found.

Treatment: Widen median

Rural two-lane roads

No studies found.

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Hauer (2000) (*15*) reviewed eleven studies and reanalyzed the data gathered in some of the studies. Hauer concluded with no specific AMFs; however the following general conclusions concerning the safety effects of median width were documented (*15*):

- As median width increases, cross-median crashes (where an opposing vehicle is struck) decrease, particularly for medians wider than 50 ft (15 m);
- As median width increases, median-related crashes may increase, reaching a peak at around 30 ft (9 m) and then decrease for medians wider than 30 ft (9 m); and,
- The effect of increasing median width on total crashes is still in question. Simple comparative studies show no change in total crashes with width, while a single study showed a decrease in total crashes with an increase in median width.

Hauer's results for three studies are included in Exhibit 3-24 (Seamons and Smith, 1991; Hadi et al., 1995; Nystrom et al., 1997) (*15*). These three studies were selected for inclusion in this synthesis either because the original data of the study was reanalyzed, or because "major" methodological problems were not noted. It was not possible to compute standard error values.

Hauer's reanalysis of the Seamons and Smith data for freeways accounted for ADT, but was unable to account for other possible factors (e.g., median shape, inside shoulder width) (*15*).

Hadi et al. developed negative binomial cross-section models for a variety of road types and settings, for both midblock and total crashes. Hauer notes a bias due to the fact that variables were excluded from the models on the basis of statistical significance only, thus some confounding probably occurs (*15*).

Hauer's review of the Nystrom et al. (*19*) data controlled only for ADT. As Hauer notes, there was no control for other factors that would differ with median width (e.g., median type, terrain, curvature, land use, etc.). Hauer was able to develop indices of effectiveness for widening medians from 10 ft to 80 ft. Note that roads with 30 ft medians without barriers appear to have about twice as many crashes as would be predicted by traffic and length alone. Hauer goes on to say that the reason for this increase in crashes for 30 ft medians is not clear, and may not be attributable to median width alone. For example, there may be an effect of median width on operating speed, or perhaps 30 ft medians are usually of the depressed type with slopes that cause overturning (*15*).

Exhibit 3-24: Summary of study characteristics for median width

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Seamons and Smith, 1991 (*22*)	Increase median width, no median barrier, for medians ≥ 50 ft	Not reported	Freeway, 20,000 to 130,000 veh/day	Multi-vehicle cross-median impacts, all severities	$\exp(-0.041\ (MW_{after} - MW_{before}))$	Unable to compute
Hadi et al., 1995 (*10*)	Increase median width	Rural	4-lane non-freeway, 1.1K-40K	Midblock, all severities	$\exp(-.0458MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Rural	4/6-lane freeway, 5K-60K	Midblock, all severities	$\exp(-.0252MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	4-lane non-freeway, 10K-50K	Midblock, all severities	$\exp(-.0588MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	6-lane non-freeway, 10K-100K	Midblock, all severities	$\exp(-.0412MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	4-lane freeway, 4.2K-137K	Midblock, all severities	$\exp(-.0801MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	6-lane freeway, 20K-200K	Midblock, all severities	$\exp(-.0345MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Rural	4-lane non-freeway, 1.1K-40K	All crashes, all severities	$\exp(-.0688MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Rural	4/6-lane freeway, 5K-60K	All crashes, all severities	$\exp(-.0472MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	4-lane non-freeway, 10K-50K	All crashes, all severities	$\exp(-.1060MW^{0.5})$	Unable to compute
Hadi et al., 1995	Increase median width	Urban	6-lane non-freeway, 10K-100K	All crashes, all severities	No statistically significant effect	n/a
Hadi et al., 1995	Increase median width	Urban	4-lane freeway, 4.2K-137K	All crashes, all severities	$\exp(-.0926MW^{.5})$	Unable to compute

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hadi et al., 1995	Increase median width	Urban	6-lane freeway, 20K-200K	All crashes, all severities	No statistically significant effect	n/a
Nystrom et al., 1997	Increase median width, within 0 to 85 ft range, no median barriers	Not reported	Freeway, 20,000 to 130,000 veh/day	Cross-median multi-vehicle, cross-median single vehicle, and median encroachment and recovery crashes, all severities	10 ft – 0.8 20 ft – 0.9 30 ft – 1.9 40 ft – 1.4 50 ft – 0.9 60 ft – 0.8 70 ft – 0.75 80 ft – 0.75	Unable to compute

NOTE: all measurements of median width (MW) for equations in this exhibit are in feet.

Exhibit 3-25 converts the above findings to a common basis for example median widths, assuming a 10 ft median has an AMF of 1.0 (i.e., same effect as no median).

Exhibit 3-25: Summary of findings concerning AMFs for increasing median width

Road type and Crash type	Median width (ft)								
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Cross-median multi-vehicle crashes – freeways	-	-	-	-	0.20	0.13	0.09	0.06	0.04
Median-related crashes (single or multi-vehicle) – freeways	1.00	1.12	2.38	1.75	1.12	1.0	0.94	0.94	-
Total crashes 4-lane rural non-freeway	*1.00*	*0.91*	*0.85*	*0.80*	*0.76*	*0.73*	*0.70*	*0.67*	*0.65*
Total crashes 4/6-lane rural freeway	*1.00*	*0.94*	*0.90*	*0.86*	*0.83*	*0.81*	*0.78*	*0.76*	*0.74*
Total crashes 4-lane urban non-freeway	*1.00*	*0.87*	*0.78*	*0.72*	*0.66*	*0.62*	*0.58*	*0.54*	*0.51*
Total crashes 4-lane urban freeway	*1.00*	*0.89*	*0.81*	*0.75*	*0.70*	*0.65*	*0.62*	*0.59*	*0.56*

It is difficult to summarize the findings since the studies examined different road types (e.g., freeway, non-freeway), and crash types (e.g., cross-median multi-vehicle, run-off-road, total). Cross-median multi-vehicle crashes are clearly reduced by increasing median width, but the amount of estimated reduction for a given width varies significantly.

Findings concerning median-related (i.e., single or multiple vehicle crashes involving the median) are inconsistent with results for other crash types. Hauer's reanalysis of the Nystrom et al. (1997) data indicates that 20 ft to 50 ft medians have more median-related crashes than 10 ft medians, and that there is no safety benefit for these crash types except in medians of 70 ft and wider.

Perhaps the more consistent findings are for total crashes. However, it is noted that all these findings are taken from one study. Hadi et al. found that while there may be a difference between median width effects on rural freeways vs. non-freeways, the effects are very similar on the urban freeways and non-freeways studied.

Neuman et al. report that "Knuiman et al. (1993) (*21*) found that accident rates continued to decrease as median widths increased up to about 80 feet (25 m). The effect was seen for head-on/opposite direction sideswipe crashes, as expected. A similar effect was also found for single- and multiple-vehicle crashes." (*16*). No comment was made by Neuman et al. about the effect of median widths wider than 80 ft (25 m). It is not clear if a distinction was made here between multiple-vehicle crashes and head-on/opposite direction crashes.

Harkey et al. (2008) utilized a cross-sectional analysis of HSIS data to develop AMF values over a range of roadway types and conditions. The results account for area type (rural vs urban), access-control (full access vs partial or no access) and provide AMFs for both total crashes and cross-median crashes. It is also important to note that the data set used to develop the AMFs did not include barriers so the AMFs from Harkey et al. 2008, are for medians without barriers. The range of AMFs developed is consistent with previous work in this area (e.g., Knuiman et al. (1993) and Hadi et al. (1995)). The AMFs for roadways with full access control and partial or no access control are presented in Exhibits 3-26 and 3-27, respectively. The baseline condition for the AMFs is a 10 ft median.

*Exhibit 3-26: AMFs for changing median widths on full access control roadways (*168*)*

Median Width	**Rural 4 Lanes**		**Urban 4 Lanes**		**Urban 5+ Lanes**	
	All	**CM**	**All**	**CM**	**All**	**CM**
10	1.00	1.00	1.00	1.00	1.00	1.00
20	0.96	0.86	0.95	0.89	0.93	0.89
30	0.93	0.74	0.90	0.80	0.86	0.79
40	0.90	0.63	0.85	0.71	0.80	0.71
50	0.87	0.54	0.80	0.64	0.74	0.63
60	0.84	0.46	0.76	0.57	0.69	0.56
70	0.81	0.40	0.72	0.51	0.64	0.50
80	0.78	0.34	0.68	0.46	0.59	0.45
90	0.75	0.29	0.65	0.41	0.55	0.40
100	0.73	0.25	0.61	0.36	0.51	0.35
All = total crashes, all severities CM = cross median crashes, all severities						

Exhibit 3-27: AMFs for changing median widths on partial or no access control roadways (168)

Median Width	**Rural 4 Lanes**		**Urban 4 Lanes**	
	All	**CM**	**All**	**CM**
10	1.00	1.00	1.00	1.00
20	0.95	0.84	0.95	0.87
30	0.91	0.71	0.90	0.76
40	0.87	0.60	0.85	0.67
50	0.83	0.51	0.81	0.59
60	0.79	0.43	0.77	0.51
70	0.76	0.36	0.73	0.45

80	0.72	0.31	0.69	0.39
90	0.69	0.26	0.65	0.34
100	0.66	0.22	0.62	0.30
All = total crashes, all severities CM = cross median crashes, all severities				

Treatment: Change median shape or type

"Median shape" is defined here to include depressed vs. raised medians. Median slopes are briefly discussed here, with more detailed discussion with roadside geometry in Section 3.1.2.

Rural two-lane roads

No studies found.

Rural multi-lane highways; Freeways; Expressways

Based on Hauer's review of studies from 1960 to 1996, it is difficult to draw conclusions based on the few and varied studies (*15*).

With respect to the issue of raised versus depressed medians (median type), the one study reviewed by Hauer (Foody and Culp, 1974, (*23*)) provided contrasting findings. Foody and Culp concentrated on one accident type – median-related single vehicle crashes – and concluded that depressed medians were superior. Hauer notes that raised medians had lower crash rates for all other crash types, and lower fatal crash rates for all types (*15*). It is very possible that a more rigorous study of more recent data might provide a different answer. Thus no conclusion can be drawn for median type based on the available literature.

With respect to the issue of median slope, two studies reviewed by Hauer (Garner and Deen, 1976, (*24*); Miaou, 1996, (*20*)) indicate that the steeper the median slope for depressed medians, the higher the median-related crash rate. However, no quantification of safety for changes to median slopes was found in the literature.

While some of the risk factors for accidents are different for cross-median vs. run-off-road-right crashes, evidence regarding the safety effects of roadside slope is perhaps the closest one can get to median slope. Additional discussion of roadside slope can be found in Section 3.1.2.

Urban and suburban arterials

No studies found.

3.1.2. Roadside Elements

The roadside is defined as "that area between the outside shoulder edge and the right-of-way limits" (*25*).

The following sections discuss of the safety effect of various roadside characteristics. Sections include the clear roadside concept, roadside geometry (including sideslopes and ditches, for roadsides and median), roadside features (such as signs, supports, and utility poles), and roadside barriers. Two tools for improving roadside safety are also discussed: the Roadside Safety Analysis Program (RSAP), and the Roadside Hazard Rating method.

The AASHTO Roadside Design Guide (*25*) is an invaluable resource for roadside design, including clear zones, geometry, features and barriers.

3.1.2.1. Roadside Geometry

Roadside geometry refers to the physical layout of the area between the outside shoulder edge and the right-of-way limits, or the area between roadways of a divided highway (i.e., the roadside or the median).

A roadside environment clear of fixed objects with stable flattened slopes is intended to increase the opportunity for errant vehicles to regain the roadway safely, or come to a stop on the roadside, and reduce the chance of serious consequences. The concept of a "forgiving roadside" is detailed in Chapter 1 of AASHTO's Roadside Design Guide (*25*).

The clear zone is defined by the AASHTO Roadside Design Guide as the "total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles. This area may consist of a shoulder, a recoverable slope, a non-recoverable slope, and/or a clear run-out area" (*25*).

A well-designed clear zone will (*16*):

- Be of sufficient width that most vehicles that leave the road do not exceed its limits;
- Have up and down slopes that do not cause vehicle rollovers; and,
- Possess soil characteristics that do not lead to vehicle tripping and thus rollovers.

It is generally accepted that a wider clear zone creates a safer environment for potentially errant vehicles. However, there are often many constraints that limit the available clear zone.

Neuman et al. state that although the Roadside Design Guide implies that a "safe clear zone width" on higher-speed roads is approximately 30 ft, there is no single width that defines maximum safety. Errant vehicles may exceed any given width; speeds and roadside elements play a significant role in the dynamics of these movements. Several factors are involved in the calculation of clear zone width, such as design speed, design ADT, prevailing sideslope, and curvature. In general, "the wider the better", up to some cost-effective limit beyond which no significant number of vehicles will encroach (*16*).

The AASHTO Roadside Design Guide provides a 6-step approach to applying the clear zone concept (*25*):

1. Remove the obstacle
2. Redesign the obstacle so it can be safely traversed
3. Relocate the obstacle to a point where it is less likely to be struck
4. Reduce impact severity by using an appropriate breakaway device
5. Shield the obstacle with a longitudinal traffic barrier designed for redirection or use a crash cushion
6. Delineate the obstacle if the above alternatives are not appropriate.

The AASHTO Roadside Design Guide contains substantial information to determine the suggested clear-zone distance approximation for roadways based on traffic volumes and speeds (Figure 3.1 or Table 3.1 of that publication), as well as a decision process to determine if a treatment is suitable for a given fixed object or non-traversable terrain feature (*25*).

The AASHTO Roadside Design Guide also provides detailed information about roadside design, particularly Chapter 3: Roadside Topography and Drainage Features (*25*). This information includes:

- Foreslopes (recoverable, non-recoverable, critical)
- Backslopes
- Transverse slopes
- Drainage channels

A recoverable slope is defined as "a slope on which a motorist may, to a greater or lesser extent, retain or regain control of a vehicle. Slopes flatter than 1V:4H are generally considered recoverable" (*25*).

A traversable slope is defined as "a slope from which a motorist will be unlikely to steer back to the roadway but may be able to slow and stop safely. Slopes between 1V:3H and 1V:4H generally fall into this category" (*25*).

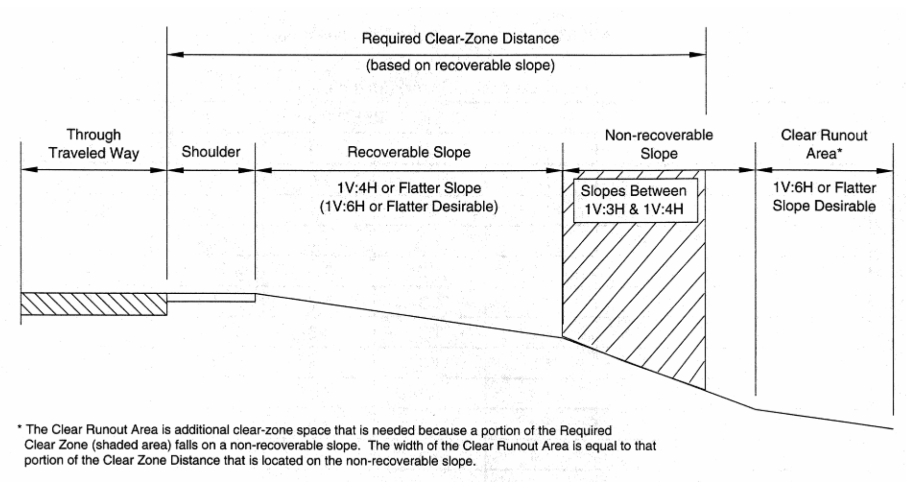
A non-recoverable slope is defined as "a slope which is considered traversable but on which the errant vehicle will continue on to the bottom. Embankment slopes between 1V:3H and 1V:4H may be considered traversable but non-recoverable if they are smooth and free of fixed objects" (*25*).

"Critical foreslopes are those steeper than 1V:3H. They will cause most vehicles to overturn" and may be candidates for treatment if the slope begins within the clear zone distance of the highway. Warrants for shielding are provided in Chapter 5 of the Roadside Design Guide (*25*).

A transverse slope is a common obstacle created by median crossovers, berms, driveways, or intersecting side roads. Transverse slopes of 1V:6H or flatter are suggested for high-speed roads, which can be transitioned to a steeper slope further from the travel lane (*25*).

A drainage channel is "an open channel usually paralleling the highway embankment and within the limits of the highway right-of-way" (*25*). These terms are illustrated in Exhibit 3-28.

Exhibit 3-28: Roadside geometry (25)



As stated in AASHTO's Policy on Geometric Design, "a curb, by definition, incorporates some raised or vertical element" (pg 323) (*26*). Curbs are used primarily on all types of low-speed urban highways (i.e., design speed less than 45 mph (70 km/h) (pg 72) (*26*)). There are two types of curb design: vertical and sloping. Vertical curbs are designed to deter vehicles from leaving the roadway. Sloping curbs (also called "mountable curbs") are designed to permit vehicles to cross them readily when needed (pg 324) (*26*). Materials that may be used to construct curbs include cement concrete, granite, and bituminous (asphalt) concrete.

While cement and bituminous concrete curbs are used extensively, it should be noted that the visibility of these types of curbs offer little visible contrast to normal pavements particularly during foggy conditions or at night when surfaces are wet. The visibility of curbs may be improved through the use of reflectorized markers that are attached to the top of the curb, or marked with reflectorized materials such as paints and thermoplastics in accordance with the guidelines outlined in the MUTCD (*26*). Delineation is discussed in Section 3.2. Curbs at intersections are discussed in Chapter 4.

This section includes discussion of the safety impact of the various roadside geometric elements discussed above. Details on other roadside elements, such as trees, poles, and barriers can be found in the following sections.

Exhibit 3-29: Resources examined to investigate the safety effect of roadside geometry on segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., R. Srinivasan, J. Baek, B. Persaud, C. Lyon, F.M. Council, K. Eccles, N. Lefler, F. Gross, E. Hauer, J. Bonneson, "Crash Reduction Factors for Traffic Engineering and ITS Improvements", NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including flattening side slopes on rural two-lane and multilane roads	Expert panel's opinions added to synthesis
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results not available.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of past studies for various road elements and safety improvements.	Provision of 95% confidence interval allows determination of standard error. Added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Strategy 15.2 B1 Design safer slopes and ditches to prevent rollovers	Strategies are discussed in ROR guide (Vol 6). No information not provided by Neuman et al., 2003. Not added to synthesis.
(*27*) (Plaxico, C. A., Ray, M. H., Weir, J. A., Orengo, F., Tiso, P., McGee, H., Council, F. M., and Eccles, K., "Recommended Guidelines for Curbs and Curb-Barrier Installations." 22-17, Washington, D.C., Transportation Research Board, National Research Council, (2004))	Study of the use of curbs and curb-barrier combinations on higher-speed roads.	No AMFs. Qualitative discussion added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*3*) (Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Used four years of HSIS crash, traffic and inventory data for urban undivided four-lane roadways in Washington State to develop cross-sectional models of safety.	Added to synthesis.
(*16*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Strategies to reduce run-off-road crashes, including minimizing the likelihood of crashing into an object or overturning if the vehicle travels off the shoulder.	Qualitative description of attributes of well-designed clear zone added to synthesis. Qualitative information and AMFS from Zegeer added to synthesis.
("Roadside Design Guide." Washington, D.C., AASHTO, (2002))	Forgiving roadside concept, detailed chapters on topography and drainage, supports, trees, barriers, bridges, barrier end treatments, control devices, etc.	Material from Chapter 1 added to section introduction (definition of clear zone concept).
(American Association of State Highway and Transportation Officials, "A Policy on Geometric Design of Highways and Streets, 4th ed. Second Printing." Washington, D.C., (2001))	Guidance for roadway designers based on established practices and recent research.	Material from Chapter 4 on clear zone added to section introduction.
(*28*) (Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Review of past literature for several road elements for two-lane rural roads.	Relationship between accident rate, ADT, and clear zone policy added to synthesis. No AMFs.
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Analysis of several roadside characteristics on about 100 km of State Route 3 in Washington State using negative binomial models.	Due to uncertainty of models with respect to the variables' individual effects, not added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	This report is a brief summary of several projects conducted in Australia.	Primarily qualitative information, quantitative values have insufficient data to determine standard error. Not added to synthesis.
(Allaire, C., Ahner, D., Abarca, M., Adgar, P., and Long, S., "Relationship Between Side Slope Conditions and Collision Records in Washington State." WA-RD 425.1, Olympia, Washington State Department of Transportation, (1996))	Naïve before/after study of 60 3R projects in Washington State.	Reviewed by Neuman et al. 2003 (Vol 6). Not added to synthesis.
(*20*) (Miaou, S. P., "Measuring the Goodness of Fit of Accident Prediction Models." FHWA-RD-96-040, McLean, Va., Federal Highway Administration, (1996))	Reviews relationship between roadside accident frequency and hazards exploring the complementary nature of accident and encroachment-based approaches	Negative binomial model results added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*29*) (Lienau, K., "Safety Effect of Barrier Curb on High Speed Suburban MultiLane Highways." TTI-04690-6, McLean, Va., Federal Highway Administration, (1996))	Used crash data in a before and after matched comparison study to evaluate the effect of barrier curb on safety; high-speed suburban multilane highways; sites in TX and IL	Suggested by NCHRP 17-18(4). Added to synthesis.
(Fambro, D. B., Nowlin, R. L., Warren, S. P., Lienau, K. A., Mounce, J. M., Bligh, R. P., Mak, K. K., and Ross, H. E., "Geometric Design Guidelines for Suburban High-Speed Curb and Gutter Roadways." FHWA/TX-95/1347-1F, College Station, Texas A&M University, (1995))	Study of geometric design elements of high-speed suburban roadways with curb and gutter. Safety study used rates, severities and frequencies.	Suggested by NCHRP 17-18(4). Same Texas data as Lienau (1996).No additional information on roadside geometry. Not added to synthesis.
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	Overview of impact on safety of various cross section elements.	Limited information. Not added to synthesis.
(Zegeer, C. V., Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume II - Alignment." FHWA-RD-91-045, Washington, D.C., Federal Highway Administration, (1992))	Primarily discussion of horizontal and vertical alignment.	AMFs for flattening sideslopes same as Zegeer et al., 1987. Not added to synthesis.
(Zegeer, C. V., Reinfurt, D. W., Hummer, J., Herf, L., and Hunter, W., "Safety Effects of Cross-Section Design for Two-Lane Roads." Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 20-32.)	This study is quoted by several of the studies reviewed above; not reviewed.	Added to synthesis as cited by (*16*).
(Zegeer, C.V., Reinfurt,D.W., Hunter,W.W., Hummer,J., Stewart,R., Herf,L., "Accident Effects of Sideslope and Other Roadside Features on Two-Lane Roads" Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 33-47)	This study is quoted by several of the studies reviewed above; not reviewed.	Added to synthesis as cited by other authors.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Summary of safety research of various traffic control and cross-section elements.	Primarily qualitative information, quantitative values have insufficient data to determine standard error. Superceded by Roadside Design Guide; not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Summary of significant findings for several cross section elements.	No additional information on roadside geometry. Not added to synthesis.

Treatment: Increase clear roadside recovery distance

Rural two-lane roads

Miaou (1996) (*20*) found that increasing the clear roadside recovery distance will have a positive safety effect on two-lane rural undivided roads (Equation 3-4). Miaou developed negative binomial regression models to accident data collected for five years on 596 sections of two-lane rural undivided road sections (totaling about 1,800 miles) in three states (Alabama, Michigan, and Washington). Miaou notes that 530 out of 596 miles of road had a posted speed limit of 55 mph, and that the 50^{th} percentile sideslope measured value of each section was used in the model development, though the actual sideslope may vary considerably within a given section. This model limitation may explain the small magnitude of effect even with substantial increases to roadside recovery distance. A baseline clear zone width and the volume range at the sites used are not specified by Miaou. A standard error is difficult to articulate for this AMF as it varies depending on clear roadside recovery distances used in the model (d1 and d2), and it is therefore not provided (t-statistic reported by Miaou (page 104) is -1.97) (*20*).

Equation 3-4: Safety effectiveness of increasing the clear zone width for single-vehicle run-off-road accidents

$$\text{AMF (single-vehicle run-off-road accidents)} = e^{-0.01375(d2-d1)}$$

Where: d2 = clear roadside recovery distance after widening (in ft)

d1 = clear roadside recovery distance before widening (in ft)

For example, using Equation 3-4, widening the clear roadside recovery distance from 5 ft to 10 ft yields an AMF for single-vehicle run-off-road accidents of:

$$\text{AMF} = e^{-0.01375(d2-d1)} = e^{-0.01375(10-5)} = 0.934$$

Zegeer et al. (1988) also estimated the effects of clear zone widening on two-lane rural roads, and calculated the expected percentage reduction of “related crashes” (i.e., the total of ROR, head-on, and sideswipe). This estimate is conditioned by the existing recovery area being less than 15 ft (4.6 m) when measured from the edgeline (Exhibit 3-30) (as cited in (*16*)). There is insufficient information to calculate the standard error of these values.

Zegeer et al. focused on a different set of target crashes; therefore, the safety effects in Exhibit 3-30 are not combined with the values from Miaou (1996). In comparing the results, it is evident that Zegeer et al. found greater safety benefits than Miaou for the same increase in clear zone width (e.g., increasing clear zone by 5 ft yields an AMF of 0.934 for Miaou, and a 13% accident reduction for Zegeer). This is likely partially due to the fact that Zegeer et al. included additional crash types, such as head-on and sideswipe, whereas Miaou modeled only single-vehicle run-off-road accidents.

Exhibit 3-30: Percent reductions in “related accidents” due to increasing the roadside clear recovery distance on two-lane rural roads (Zegeer et al., 1988 as cited in (16))

Amount of increased roadside recovery distance in ft (m)	% Reduction in related accident types (total of run-off-road, head-on, and sideswipe)
5 (1.5)	13
8 (2.4)	21
10 (3.1)	25
12 (3.7)	29
15 (4.6)	35
20 (6.2)	44

As stated by Neuman et al., “While additional guidance on [clear zone] widths and slopes and economic analysis techniques should be developed within the next 1 to 5 years, the best current guidance on widths and slopes is in the AASHTO Roadside Design Guide” (*16*).

In summary, both Miaou and Zegeer find a similar safety effect trend due to increasing clear zone distance on two-lane rural roads.

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

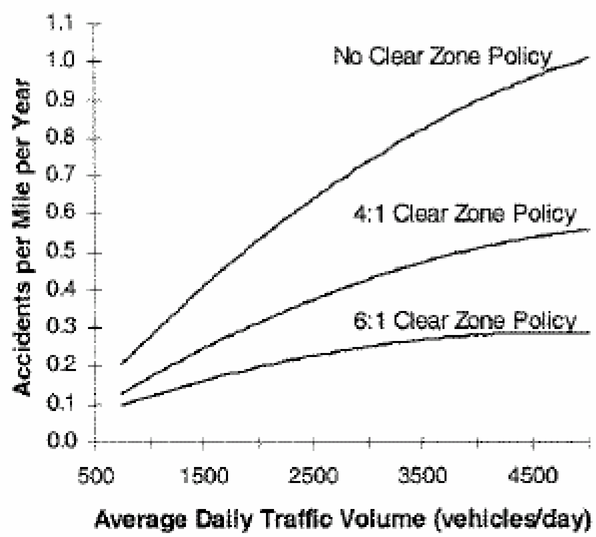
No studies found.

Treatment: Implement clear zone policy

All roads

As noted by Fitzpatrick et al., Graham and Harwood (1982) found that “single-vehicle accidents per mile per year are highest for roads with no clear zone policy, lower for a 1V:4H clear zone policy (i.e., clear area with a 1V:4H sideslope), and lowest for a 1V:6H clear zone policy for various ADTs” (*28*) (pg 59). The relationship is shown in Exhibit 3-31. Although Graham and Harwood note that the field conditions may not necessarily match the clear zone policy, the study indicates a potential for safety benefits from increased clear zones and flatter sideslopes. Although not noted by Fitzpatrick et al., or Graham and Harwood, it is also possible that the roads with smaller clear zones used lower design standards which may have confounded the results noted here (e.g. narrow lanes, no pavement markings, etc.).

Exhibit 3-31: Relationship between single-vehicle accident rate (run-off-road; per mile per year) and ADT for two-lane highways with various clear zone policies (28)



Discussion: Safety effect of increased clear zone

Other information about clear zone safety effect found in current literature is summarized here.

Fambro et al. (1995) used benefit-cost approach for clear zone guidelines on suburban high-speed (50 or 55 mph posted speed limit) roadways with curb and gutter, focused on roadways with growth in traffic volume and turning movements requiring widening of existing two-lane highway to four or more lanes. Baseline minimum clear zone was 10 ft (3 m) after widening. Study found that the following scenarios are not cost-beneficial:

- To purchase 5 ft (1.5 m) or less of additional right-of-way (with existing clear zone of 10 ft or more) primarily due to high cost of relocation of utility poles
- To purchase of additional right-of-way for costs greater than $4 / ft2 ($43.06 / m2)
- To provide more than the 10 ft baseline clear zone for roadways with low roadside hazard rating

However, the benefit for avoiding a fatality was estimated to be $500,000 for this analysis, a value that is much higher today and would likely change the conclusions (*16*).

Treatment: Flatten sideslopes

Rural two-lane roads

Elvik and Vaa (*8*) found that flattening sideslopes "reduces both the number and severity of accidents" based on three American studies (Dotson, 1974; Missouri Dept of Transportation, 1980; Graham and Harwood, 1982). The index of effectiveness is as given by Elvik and Vaa; the standard error is based on the 95% confidence interval, with a method correction factor of 1.8.

Miaou also found that a "steeper sideslope is associated with a higher single-vehicle run-off-road accident rate" on two-lane rural roads (*20*). Miaou notes that the 50th percentile sideslope measurement was used, though the actual sideslope may vary considerably within a given section. This study was rated medium-high and assigned a method correction factor of 1.5.

These two studies provide the only AMFs found with sufficient information to provide estimates of their standard errors (Exhibit 3-32 and Exhibit 3-33).

Exhibit 3-32: Safety effectiveness of flattening sideslopes from 1V:3H to 1V:4H (8) (20)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik, 2004	Flatten sideslope from 1V:3H to 1V:4H	Rural	Mostly two-lane, volume unknown	All types, injury	0.58	0.036
Elvik, 2004	Flatten sideslope from 1V:3H to 1V:4H	Rural	Mostly two-lane, volume unknown	All types, PDO	0.71	0.036
Miaou, 1996	Flatten sideslope from 1V:3H to 1V:4H	Rural	Two-lane, unknown volume	Single-vehicle run-off-road, all severities	0.82	0.159

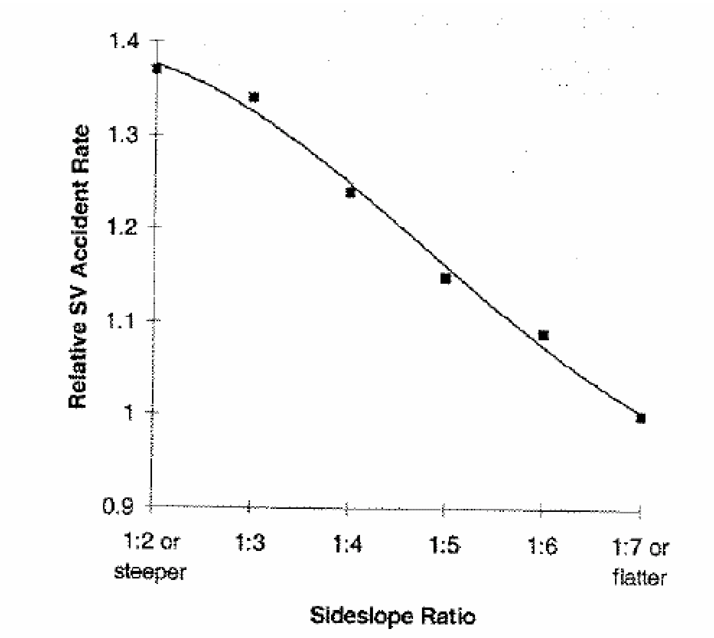
Exhibit 3-33: Safety effectiveness of flattening sideslopes from 1V:4H to 1V:6H (8) (20)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik, 2004	Flatten sideslope from 1V:4H to 1V:6H	Rural	Mostly two-lane undivided, volume unknown	All types, injury	0.78	0.036
Elvik, 2004	Flatten sideslope from 1V:4H to 1V:6H	Rural	Mostly two-lane undivided, volume unknown	All types, PDO	0.76	0.023
Miaou, 1996	Flatten sideslope from 1V:4H to 1V:6H	Rural	Two-lane undivided, unknown volume	Single-vehicle run-off-road, all severities	0.76	0.208

The following studies provide additional qualitative knowledge with some indices of effectiveness, but have insufficient information to determine the standard error of the estimates.

Zegeer et al. (1987) estimated the relationship between single-vehicle accidents and field-measured sideslopes (Exhibit 3-34), as cited in (*28*).

Exhibit 3-34: Relationship between single-vehicle accident rate and sideslope, relative to accident rate for a sideslope of 7:1 [1V:7H] or flatter (Zegeer et al., 1987 as cited by (28))



Note: Sideslope Ratios in Exhibit 3-34 are referring to a V:H relationship

Zegeer et al. (1987) examined sideslope effects on rollover and all single-vehicle ROR crashes using field-measured data from approximately 1,800 miles of rural two-lane roads in three states. Neuman et al. report that “the authors found that rollover rates were significantly higher on slopes of 1[V]:4[H] or steeper as compared with slopes of 1[V]:5[H] or flatter … it is concluded that single-vehicle ROR crashes (which include, but are not limited to, rollovers) can be significantly reduced by flattening existing sideslopes to 1[V]:4[H] or flatter”. Neuman et al. also find that “the corresponding decrease in total crashes for this example is an estimated 15 percent. These estimates are made under the assumption that the clear zone width stays the same and that the resulting sideslope is relatively free of rigid objects”, based on Zegeer et al. (Exhibit 3-35) (as cited in (*16*)).

Allaire et al. (1996) studied sideslope flattening projects and ROR collision frequency and severity using a before-after study of 60 projects that involved sideslope flattening for at least some portion of the project. By comparing to “control” changes, Allaire et al. found a statistically significant benefit for slope flattening. “The percent reduction in ROR collision rates varied by comparison and by injury severity class from approximately 3 to 50 percent. Based upon examination of the tables, the estimated “median” reduction in ROR crash rate is approximately 25 to 45 percent.” (as cited in (*16*)).

Exhibit 3-35: Percentage reduction of single-vehicle and total crashes due to sideslope flattening on two-lane rural roads (Zegeer et al., 1987 as cited by (16)).

Sideslope Before Condition	Sideslope After Condition							
	1:4		1:5		1:6		1:7 or Flatter	
	SV	Total	SV	Total	SV	Total	SV	Total
1:2	10	6	15	9	21	12	27	15
1:3	8	5	14	8	19	11	26	15
1:4	0	-	6	3	12	7	19	11
1:5	-	-	0	-	6	3	14	8
1:6	-	-	-	-	0	-	8	5

Note: Sideslope Ratios in Exhibit 3-35 are referring to a V:H relationship

An expert panel was convened as part of Harkey et al. (2008) to determine the best available AMF values for changing roadside sideslopes. The expert panel’s assessment was that the AMFs developed by Zegeer et al. (see Exhibit 3-35) are the most accurate, consistent, and cover more cases than other research.

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

The expert panel on rural multilane highways convened as part of Harkey et al. (2008) concluded that the AMFs from Zegeer et al. (1987) were valid and the best available for both rural two-lane roads and rural multilane highways. The discussion of this study and recommended results are found above for rural two-lane roads.

Treatment: Install vertical curb instead of parallel drainage ditch design

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Using data from Washington State (1993 to 1996), multivariate statistical models were developed by Hauer et al. in order to predict the non-intersection accident frequency of urban four-lane undivided roads (*3*). Six separate models were estimated for "off-the-road" and "on-the-road" property damage only (PDO), Injury, and Total accidents. "Off-the-road" accidents were identified using the Impact Location Code in the HSIS database on which the models were derived. Accidents occurring "Off Road Past Shoulder" and "On Shoulder" were classified as off-the-road accidents. The traffic volumes for the sites studied had a range of 2,500 to 68,500 veh/day with the mean being 24,900 veh/day (*3*). Hauer et al. categorized shoulders as either curb/wall, or flush of various widths.

Based on the results from the study by Hauer et al., it appears that the presence of curbs instead of narrow flush shoulders results in increased crashes. The study results are summarized in Exhibit 3-36. There were insufficient data to calculate standard error values for these values.

Exhibit 3-36: Safety effectiveness of raised curbs on urban four-lane undivided roads (3)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hauer et al., 2004	Curbs instead of 2 to 3 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	Off-the-road accidents, PDO	1.38	Unable to calculate.
Hauer et al., 2004	Curbs instead of 2 to 3 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	Off-the-road accidents, Injury	1.25	Unable to calculate.
Hauer et al., 2004	Curbs instead of 2 to 3 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	Off-the-road accidents, Total	1.32	Unable to calculate.
Hauer et al., 2004	Curbs instead of 2 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	On-the-road accidents, PDO	1.19	Unable to calculate.
Hauer et al., 2004	Curbs instead of 2 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	On-the-road accidents, Injury	1.08	Unable to calculate.

Hauer et al., 2004	Curbs instead of 2 ft flush shoulders	Urban Washington	Four-lane undivided, 2,500 to 68,500 veh/day	On-the-road accidents, Total	1.13	Unable to calculate.

Lienau et al. (1996) attempted to quantify the safety effects of barrier curb (i.e., vertical curb) on high-speed suburban multilane highways, compared with a rural parallel drainage ditch design (*29*). Using TXDOT and HSIS data, Lienau et al. studied sites in Texas and Illinois.

The Texas data comprised 10 sections, varied in length and driveway density, with at least two through lanes in each direction. The posted speed limit of all sections was 50 mph or greater, none had paved shoulders, one had a flush median, two had a raised median, and six had TWLTL; volumes ranged from 5,900 to 18,300 veh/day. A minimum of two years of before and two years of after data were included in the analysis (*29*).

The Illinois data comprised nine multilane (non-freeway) sections with curb and gutter, and homogeneous volumes, median design, and number of lanes for comparative analysis. Comparison sites were then matched to these nine sections. The curbed study sites had posted speed limits of 50 mph or greater, none had shoulders, one had a curbed median, one had a mountable median, one had an unprotected median, two had rumble strip medians, and four had no median; volumes ranged from 14,500 to 34,900 veh/day. The comparison sites had similar characteristics (*29*).

Lienau et al. used accident rates before/after curb installation in Texas, and with/without curbs in Illinois. The accident frequencies are also provided in an appendix to their report. However, the AADT and length of each site is not reported; therefore, the best estimate of an AMF from these studies was determined from the accident rates computed by Lienau et al. (accidents/mile/year) (*29*), and are summarized in Exhibit 3-37. The indices of effectiveness were calculated by taking the arithmetic average of the results of the sites for each method (i.e., Texas and Illinois results were kept separate), and estimates of standard error for each method were based on Equation 3-1, where n=10 for Texas and n=9 for Illinois, and x_i is the change in accident rate at each site. A method correction factor of 3 was then applied, as the study does not account for confounding factors (e.g., driveway density, volumes, etc.), and the small sample sizes used in the study.

Note that the large standard error for the Illinois data (26.48) is primarily due to one set of sites where the non-curbed site experienced 3.08 acc/mi/yr and the curbed site experienced 83.39 acc/mi/yr (Exhibit 3-37). The factors involved in this substantial difference in crash experience are unclear, but it skews the Illinois results. In an attempt to learn from the study results, the Illinois data were reanalyzed excluding that site; however, the standard error is still large.

Exhibit 3-37: Safety Effectiveness of raised curbs on high-speed suburban multi-lane highways (non-freeways) (29)

Author, date	**Treatment / Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**

Lienau et al., 1996	Barrier curb on the road edge	Suburban Texas	Multilane highways, 5,900 to 18,300 veh/day	All accidents, all types	1.09	1.26
Lienau et al., 1996	Barrier curb on the road edge	Suburban Illinois	Multilane highways, 14,500 to 34,900 veh/day	All accidents, all types	3.57	26.48
Lienau et al., 1996	Barrier curb on the road edge	Suburban Illinois	Multilane highways, 14,500 to 34,900 veh/day	All accidents, all types*	0.64*	1.64*

* One set of sites where the non-curbed site experienced substantially fewer accidents than the curbed site was removed from this calculation

Treatment: Install curb-barrier system

All roads

Plaxico et al. studied curbs and curb-barrier systems along roads with operating speeds greater than 60 km/h (*27*). Guidelines were developed as a result of the study, such as (page 151):

- *"When curbs must be used on high-speed roads, the smallest possible curb height and flattest slope should be used in order to minimize the risk of tripping the vehicle in a non-tracking collision"*
- *"Any combination of a sloping-faced curb that is 150 mm or smaller and a strong-post guardrail can be used where the curb is flush with the face of the guardrail up to an operating speed of 85 km/h"*
- *"Guardrails installed behind curbs should not be located closer than 2.5 m for any operating speed in excess of 60 km/h"*

Additional guidelines are provided in that document regarding the implementation of curbs and curb-barrier systems. However, no quantification of safety effect was reported (*27*).

3.1.2.2. Roadside Features

Roadside features may include signs, signals, luminaire supports, utility poles, trees, motorist-aid call boxes, railroad crossing warning devices, fire hydrants, mailboxes, and other similar roadside features.

The AASHTO Roadside Design Guide contains information about the placement of these features, criteria for breakaway supports, base designs, etc. (*25*).

Providing barriers in front of roadside features that cannot be relocated is discussed in Section 3.1.2.3.

A discussion of the safety effects of illumination pole positions will take place here while the safety effect of the presence of illumination is found in Section 3.4.1.

Exhibit 3-38: Resources examined to investigate the safety effect of roadside features on segments

DOCUMENT	DESCRIPTION	COMMENT

DOCUMENT	DESCRIPTION	COMMENT
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	15.2 B2 Remove/relocate objects in hazardous locations 15.2 B4 Add or improve roadside hardware	These strategies are discussed in the Run-off-Road guide (Vol 6) – see below. Not added to synthesis.
(*30*) (Lacy, K., Srinivasan, R., Zegeer, C. V., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 8: A Guide for Addressing Collisions Involving Utility Poles." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies to mitigate crashes with utility poles.	Qualitative discussion of strategies. No AMFs. Limited information added to synthesis.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of past studies for various road elements and safety improvements.	AMFs for removing and marking roadside obstacles. Added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Lacy, K., and Zegeer, C., "NCHRP Report 500 Volume 3: A Guide for Addressing Collisions with Trees in Hazardous Locations." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2003))	16.1 B4 Delineate Trees in Hazardous locations 16.1 B1 Remove trees in hazardous locations	Qualitative discussion of strategies. Not added to synthesis.
(*16*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Strategies to reduce run-off-road crashes, including minimizing the likelihood of crashing into an object or overturning if the vehicle travels off the shoulder.	Qualitative information on feature placement added to synthesis. AMFs found by Zegeer 1990 added to synthesis.
(Mak, K. K. and Sicking, D. L., "NCHRP Report 492: Roadside Safety Analysis Program (RSAP) - Engineer's Manual." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Discussion of RSAP software and approach.	No information relevant to this section, used in section on RSAP. Not added to synthesis.
("Roadside Design Guide." Washington, D.C., AASHTO, (2002))	Guidebook that readers may refer to.	Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Review of past literature for several road elements for two-lane rural roads.	No new information – all provided by other references. Not added to synthesis.
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Analysis of several roadside characteristics on about 100 km of State Route 3 in Washington State using negative binomial models.	Due to uncertainty of models with respect to the variables' individual effects, not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Allaire, C., Ahner, D., Abarca, M., Adgar, P., and Long, S., "Relationship Between Side Slope Conditions and Collision Records in Washington State." WA-RD 425.1, Olympia, Washington State Department of Transportation, (1996))	Naïve before/after study of 60 3R projects in Washington State.	Reviewed by Neuman et al. 2003 (Vol 6). Not added to synthesis.
(Miaou, S. P., "Measuring the Goodness of Fit of Accident Prediction Models." FHWA-RD-96-040, McLean, Va., Federal Highway Administration, (1996))	The study reviews the relationship between roadside accident frequency and hazards exploring the complementary nature of accident and encroachment-based approaches	Roadside features were not modeled. Not added to synthesis of this section. Relevant info added to syntheses of other roadside sections.
(Zegeer, C. V., Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume II - Alignment." FHWA-RD-91-045, Washington, D.C., Federal Highway Administration, (1992))	Primarily discussion of horizontal and vertical alignment.	AMFs for increased roadside recovery distance. Information insufficient to calculate standard error; no baseline given. Not added to synthesis.
(*31*) (Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	Overview of impact on safety of various cross section elements.	No new information on roadside geometry. Not added to synthesis.
(Zegeer, C. V., Reinfurt, D. W., Hummer, J., Herf, L., and Hunter, W., "Safety Effects of Cross-Section Design for Two-Lane Roads." Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 20-32.)	This study is quoted by several of the studies reviewed above; not reviewed.	Results included in meta-analysis by Elvik and Vaa (2004).
(*32*) (Zegeer, C.V., Reinfurt,D.W., Hunter,W.W., Hummer,J., Stewart,R., Herf,L., “Accident Effects of Sideslope and Other Roadside Features on Two-Lane Roads” Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 33-47)	This study is quoted by several of the studies reviewed above; not reviewed.	Added to synthesis as cited by other authors.
(*33*) (Zegeer, C. V. and Cynecki, M. J., "Determination of Cost-Effective Roadway Treatments for Utility Pole Accidents." Transportation Research Record 970, Washington, D.C., Transportation Research Board, National Research Council, (1984) pp. 52-64.)	Article summarizing the development of a model to predict utility pole accidents based on ADT, pole density, and pole offset.	Model results added to synthesis.
(*34*) (Zegeer, C. V. and Parker, M. R., Jr., "Effect of Traffic and Roadway Features on Utility Pole Accidents." Transportation Research Record 970, Washington, D.C., Transportation Research Board, National Research Council, (1984) pp. 65-76.)	Article summarizing various costs for utility pole countermeasures.	Roadside adjustment factor for model results added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Summary of safety research of various traffic control and cross-section elements.	Primarily qualitative information, quantitative values have insufficient data to determine standard error. Not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Summary of significant findings for several cross section elements.	No additional information on roadside geometry. Not added to synthesis.

Discussion: Roadside features in the clear zone area

Neuman et al. state, "The clear zone concept requires that no objects that can result in crashes be located in the zone" (*16*). It is recognized that there is often a need for some objects to be located in the desired clear zone, such as sign supports, barriers, culverts, or utility poles. "Regardless of the reason, the best treatment for all objects is to remove them from the zone." Neuman et al. suggest that if this cannot be done, alternative strategies include:

- Relocating the objects either farther from the traffic flow or to less hazardous locations
- Shielding or replacing "harder" objects with less hazardous breakaway devices

Information about the implementation of these strategies can be found in the AASHTO Roadside Design Guide (*25*).

The Code of Federal Regulations [23 CFR 645.209(k)] requires that when a transportation agency "determines that existing utility facilities are likely to be associated with injury or accident to the highway user, as indicated by accident history or safety studies, the transportation department shall initiate or cause to be initiated in consultation with the affected utilities, corrective measures to provide for a safer traffic environment" (*35*).

Treatment: Increase the distance to roadside obstacles

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Elvik and Vaa estimated the safety effect for increasing the distance to roadside obstacles, based on American studies by Cirillo (1967) and Zegeer et al. (1988). It is unclear if the distance is measured from the travel lane or shoulder edge for the Cirillo study, but the Zegeer et al. study notes that the distance was measured from the edgeline or edge of the travel lane(*32*). The road types, traffic volumes, and environments were reported as noted in Exhibit 3-39. It is noted that only two studies are included in this exhibit. Elvik and Vaa state that it is unknown if the results include the effect of other improvements, such as improved sight distance (*8*). The estimates of standard error are calculated based on the 95% C.I. reported by Elvik and Vaa, multiplied by a method correction factor of 1.8.

Exhibit 3-39: Safety effects of increased distance to roadside features (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik, 2004	Increase distance to obstacle from around 1 m to around 5 m	Rural	Mixture of freeways and two-lane, volume unknown	All types, unknown severity	0.780	0.018
Elvik, 2004	Increase distance to obstacle from around 5 m to around 9 m	Rural	Mixture of freeways and two-lane, volume unknown	All types, unknown severity	0.560	0.014

Note: Distance measured from the edgeline or edge of travel lane.

Zegeer et al. (1992) provides percent accident reduction values for increased roadside recovery distance (which is defined by those authors as including removing trees, relocating utility poles and other obstacles, providing traversable drainage structures, and flattening roadside slopes) (*31*). However, a baseline for these values is not provided, and more recent studies have indicated that the benefit of widening the roadside recovery distance depends not only on the amount of widening, but also the amount of recovery distance prior to widening. Therefore, the results of Zegeer et al. (1992) are not included in this synthesis.

Zegeer et al. (1990) developed safety effectiveness estimates for removing roadside hardware from the clear zone or relocating it farther from the travel way for two-lane rural roads (Exhibit 3-40). These estimates are based on the assumption that removing a specific object increases the clear zone width, and that other objects do not remain at the distance that the specific object was moved from (close to the travel way) (*16*). There is insufficient information to calculate standard errors for these AMFs. The traffic volumes and other cross-sectional elements for these values are unknown.

Exhibit 3-40: AMFs for specific types of obstacle accidents due to clearing/relocating obstacles farther from the roadway on two-lane rural roads (Zegeer et al., 1990 as cited in (16))

Increase in obstacle distance in ft (m)	Trees	Mailboxes, culverts, and signs	Guardrails	Fences/Gates
3 (0.9)	0.78	0.86	0.64	0.80
5 (1.5)	0.66	0.77	0.47	0.70
8 (2.4)	0.51	0.66	0.30	0.56
10 (3.1)	0.43	0.60	0.22	0.48
13 (4.0)	0.34	NF	NF	NF
15 (4.6)	0.29	NF	NF	NF

Notes: NF = generally not feasible to relocate obstacles to specified distance.
These values are only appropriate for obstacle distance of 30 ft or less on two-lane rural roadways.

The values developed by Zegeer et al. are somewhat counterintuitive, as it seems reasonable to expect that the magnitude of safety effect will vary depending how far away the obstacle is from the roadway prior to relocation, not just on the increase in obstacle distance. In other words moving a mailbox from 3 ft to 8 ft is likely more beneficial than moving the same mailbox from 8 ft to 13 ft.

Discussion: Remove roadside obstacles

Elvik and Vaa cite an Australian study (Corben et al., 1997) that investigated the impact of removing roadside obstacles. This study found an index of effectiveness of 0.98 (S=0.3, based on 95% C.I. given by Elvik and Vaa and a method correction factor of 3 due to the lack of detail known about the Corben study) for all accident types of injury severity. The road type, volume, and environment are not stated. The results of the study were not statistically significant (*8*).

No other AMFs were found for the removal of roadside obstacles.

Treatment: Increase the distance to utility poles and decrease utility pole density

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Zegeer and Parker (1984) (*34*) and Zegeer and Cynecki (1984) found that crashes decrease as pole offsets are increased, and as pole density is reduced (*30*) based on a predictive model using 9,600 utility pole crashes in four states, which relates the number of pole crashes to the average offset from the travel lane, ADT, and pole density. Substantial effects were observed by relocating the poles at least 10 ft from the roadway. As the offset (distance between roadway edgeline and utility pole) increases beyond 10 ft, the safety benefit continues to increase, but at a slower rate. The best-fit regression model is provided here as Equation 3-5.

Equation 3-5: Utility pole accident predictive model (33)

$$Acc/mi/yr = ([9.84 \times 10^{-5} (ADT) + 3.54 \times 10^{-2} (Density)] / (Offset)^{0.6}) - 0.04$$

Where:

Acc/mi/yr = number of predicted utility pole accidents per mile (1.6 km) per year

ADT = annual average daily traffic volume

Density = number of utility poles per mile within 30 ft (10 m) of the roadway

Offset = average lateral offset of the utility poles (ft) from the roadway edge

Note: It is not indicated if the model is intended for two-lane or multilane, rural or urban settings.

The above model can be used for any combination of ADT, pole density or pole offset. An AMF can be calculated by taking the ratio of the approximate frequency of predicted accidents (acc/mi/yr) with the after conditions divided by the observed accidents (acc/mi/yr) with the before conditions, assuming no significant changes in traffic volumes. For example, Exhibit 3-41 shows the expected safety effect as poles are moved away from the roadway for ADT of 10,000 veh/day and pole density of 40 poles/mile. These AMFs assume that no other roadside fixed objects are present apart from the utility poles.

Exhibit 3-41: AMFs for utility poles accidents for moving poles farther from the roadway (Zegeer and Cynecki, 1984 as cited in (30))

Pole offset before (ft)	**Pole offset after (ft)**								
	6	**8**	**10**	**12**	**15**	**17**	**20**	**25**	**30**
2	0.50	0.42	0.36	0.32	0.28	0.26	0.23	0.20	0.18
3	0.65	0.54	0.47	0.42	0.36	0.33	0.30	0.26	0.23
4	0.78	0.65	0.56	0.50	0.43	0.40	0.35	0.31	0.27
5	0.89	0.74	0.64	0.57	0.49	0.45	0.41	0.35	0.31
6		0.83	0.72	0.64	0.55	0.51	0.46	0.39	0.35
7		0.92	0.80	0.71	0.61	0.56	0.50	0.43	0.38
8			0.87	0.77	0.67	0.61	0.55	0.47	0.42
10				0.89	0.77	0.71	0.63	0.55	0.48
11				0.95	0.82	0.75	0.67	0.58	0.51
12					0.86	0.80	0.71	0.61	0.54
13					0.91	0.84	0.75	0.65	0.57
14					0.96	0.88	0.79	0.68	0.60
15						0.92	0.83	0.71	0.63

NOTE: Pole offset is defined as the distance between the roadway edgeline and the utility pole.

To account for the presence of other roadside objects, Zegeer and Cynecki (1984) developed adjustment factors, which adjust the predicted utility pole accidents for various types of roadsides and the presence of other fixed objects along the road. An example of roadside adjustment factors for placing poles underground, increasing lateral pole offsets, and reducing pole density through multiple pole use is shown in Exhibit 3-42.

Exhibit 3-42: Roadside adjustment factors for placing utility lines underground, increasing lateral offsets, and multiple pole use; for use in conjunction with Exhibit 3-41 (33)

Utility Lines Undergrounding

Pole Offset	Rural Areas			Urban Areas		
	Coverage of Fixed-Objects			Coverage of Fixed-Objects		
(Feet)	10%	35%	60%	10%	35%	60%
2	0.619	0.497	0.374	0.706	0.574	0.443
5	0.611	0.486	0.361	0.670	0.513	0.356
10	0.564	0.433	0.295	0.611	0.441	0.271
15	0.543	0.407	0.241	0.530	0.383	0.236
20	0.521	0.376	0.231	0.400	0.289	0.178
25	0.471	0.340	0.210			
30	0.400	0.289	0.178			

Increasing Lateral Pole Offset

Pole Offset (Feet)		Area Type	Coverage of Fixed-Objects		
Before Improvement	After Improvement	(Urban or Rural)	10%	35%	60%
2	30	R	0.716	0.589	0.461
5	30	R	0.708	0.576	0.445
10	30	R	0.661	0.509	0.357
15	30	R	0.650	0.469	0.277
20	30	R	0.650	0.469	0.289
25	30	R	0.650	0.469	0.289
2	20	R	0.763	0.672	0.582
5	20	R	0.703	0.655	0.560
10	20	R	0.672	0.548	0.423
15	20	R	0.650	0.469	0.289
2	20	U	0.833	0.693	0.552
5	20	U	0.816	0.634	0.452
10	20	U	0.800	0.578	0.356
15	20	U	0.800	0.578	0.356
2	10	U	0.861	0.791	0.721
5	10	U	0.840	0.718	0.596

Multiple Pole Use

Pole Offset	Rural Areas			Urban Areas		
	Coverage of Fixed-Objects			Coverage of Fixed-Objects		
(Feet)	10%	35%	60%	10%	35%	60%
2	0.619	0.497	0.374	0.823	0.659	0.495
5	0.611	0.486	0.361	0.810	0.614	0.418
10	0.571	0.433	0.295	0.800	0.578	0.356
15	0.543	0.392	0.241	0.800	0.578	0.356
20	0.521	0.376	0.231			
25	0.471	0.340	0.210			
30	0.400	0.289	0.178			

Note: 1 foot = 0.3 m

NCHRP Report 500 Volume 8 has identified several other strategies to address crashes involving utility poles (*30*). Details on these strategies are not repeated here. AMFs are not available.

Discussion: Use breakaway devices

The use of breakaway devices may be considered if relocating or removing the poles is not feasible or cost-effective and the location of the pole meets the following criteria (*30*):

- Pole is located in the clear zone
- Alternatives for removing or relocating the pole is not practical due to right-of-way, roadside, or economic constraints
- Pole is class 4-40 or smaller and does not have attached heavy devices
- There is a safe recovery area behind the pole, free of roadside hazards
- Pole is not located near a zone of significant pedestrian activity
- Final position of pole and conductors (wires) should not create a hazard for pedestrians, other vehicles, and adjacent property owners

AMFs were not found for the introduction of breakaway utility poles.

Discussion: Delineate roadside features

Elvik and Vaa report the only quantified safety effect for marking roadside obstacles to increase their visibility based on a study conducted in Australia (Corben et al., 1997). An index of effectiveness of 0.77 (s=1.01, based on 95% C.I. reported by Elvik, multiplied by MCF of 3 due to lack of detail reported for the original study) is provided for injury accident for all types; the results of the study are not statistically significant (*8*). The road type, volume, and environment are not stated. “At least two states are currently pilot testing a low-cost experimental strategy where roadside objects are delineated so that they are more visible to drivers at night” (*16*). Pennsylvania and Iowa are testing a strategy at sites where it is not feasible to remove or relocate the objects (utility-poles, trees). The effectiveness of this delineation has not yet been quantified; it is unknown if this treatment will be beneficial or confusing to road users. The hypothesis is that the added delineation could provide additional guidance to drivers to assist in maintaining the travel way, make the hazard more visible, or provide information to allow the driver to navigate the roadside (assuming the driver is able to react and control the vehicle after leaving the travel way). “This should not be used in place of other non-experimental treatment and should be pilot tested and evaluated before widespread use in any jurisdiction” (*16*)

Lacy et al. provide some discussion regarding the safety effect of delineating poles to improve the drivers’ ability to see poles in high-crash locations. “A major problem with this strategy is that its low cost may make it appear attractive, but it may not provide any real improvement in safety. Application of this strategy should be limited to poles where other strategies cannot be applied” (pg V-19) (*30*).

3.1.2.3. Roadside Barriers

As defined by AASHTO’s Roadside Design Guide, a roadside barrier (guardrail, guiderail) is “a longitudinal barrier used to shield motorists from natural or man-made obstacles located along either side of a traveled way. It may also be used to protect bystanders, pedestrians, and cyclists from vehicular traffic under special conditions” (*25*). This section will discuss the safety effect of implementing roadside barriers to provide a buffer between motorists and roadside features (Roadside Features are discussed in Section 3.1.2.2). Median barriers are included in this discussion. Bridge railings are not included in this discussion; the reader is referred to Section 6.3 Bridges [Future Edition]. Clear zone, roadside geometry, roadside features, use of the Roadside Safety Analysis Program, and applying the roadside hazard rating are discussed later.

At this time, no literature was found describing the safety effect of the use of roadside barriers to protect bystanders, pedestrians, and bicyclists. Future editions of the HSM may discuss this treatment.

Warrants for barrier installation can be found in AASHTO's Roadside Design Guide, along with performance requirements, placement guidelines, and a methodology for identifying and upgrading existing installations (*25*).

Barrier end treatments or terminals are "normally used at the end of a roadside barrier where traffic passes on one side of the barrier and in one direction only. A crash cushion is normally used to shield the end of a median barrier or a fixed object located in a gore area. A crash cushion may also be used to shield a fixed object on either side of a roadway if a designer decides that a crash cushion is more cost-effective than a traffic barrier" (*25*). A crashworthy end treatment is considered valuable if a roadside barrier terminates within the clear zone or an area likely to be struck by errant vehicles. "Crashworthy" implies that the end treatment "should not spear, vault, or roll a vehicle for head-on or angled impacts" (*25*).

AASHTO's Roadside Design Guide contains barrier end treatment and crash cushion installation warrants, structural and performance requirements, selection guidelines, and placement recommendations (*25*).

Exhibit 3-43: Resources examined to investigate the safety effect of roadside barriers on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of the safety effect of placing guardrails along the roadside; placing guardrails in the median of divided highways; guardrails placed between opposing lanes of undivided highways; crash cushion installation	Results for roadside, divided median, undivided median and crash cushions added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	15.2 B5 Improve design and application of barrier and attenuation systems	Strategies are fully discussed in Vol 6 (ROR guide). Not added to synthesis.
(*16*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	15.1 C2 Improve Design and Application of Barrier and Attenuation Systems	Discussion of past research added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*36*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Lacy, K., and Zegeer, C., "NCHRP Report 500 Volume 3: A Guide for Addressing Collisions with Trees in Hazardous Locations." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2003))	16.1 B2 Shield motorists from striking trees	Qualitative discussion added to synthesis. No quantitative information
Srinivasan, Raghavan.; Lacy, Kevin.; Feaganes, John.; and Hunter, William. Effects of Continuous Median Barriers on Highway speeds, emergency response times, and Transport Times on North Carolina Highways. Final Report, FHWA A/NC/2003-05, November 2003.	This study examines the effect of various types of median barriers in terms of speeding, speeding related crashes and emergency response time. 51 freeway segments with 4 types of median barriers were studied.	Statistical models were calibrated to help predict collision frequency at any one of the 4 median types. No AMFs. Not added to synthesis.
("Roadside Design Guide." Washington, D.C., AASHTO, (2002))	Guidebook that contains substantial information on barriers and roadside design.	No AMFs. Not added to synthesis.
(*37*) (Ray, M. H., Weir, J., and Hopp, J., "In-Service Performance of Traffic Barriers." 22-13, Washington, D.C., Transportation Research Board, National Research Council, (2002))	In-service safety performance evaluation of common guardrails and guardrail terminals in NC, IA, and CT	Suggested by NCHRP 17-18(4). No information about overall impact on safety. Not added to synthesis.
(*38*) (Hunter, W. W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M., and Harkey, D. L., "Three-Strand Cable Median Barrier in North Carolina: In-Service Evaluation." Transportation Research Record, No. 1743, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 97-103.)	Used crash data to evaluate the effect of the installation of cable median barrier on crash rates in NC; only used Interstate locations	Suggested by NCHRP 17-18(4). Insufficient information to determine safety effect. Not added to synthesis.
(*15*) (Hauer, E., "The Median and Safety." (2000))	Addresses the use of guardrail as a median barrier	Suggested by NCHRP 17-18(4). Added to synthesis.
(*39*) (Ray, M. H., "Safety Effectiveness of Upgrading Guardrail Terminals to Report 350 Standards." Transportation Research Record, No. 1720, Washington, D.C., Transportation Research Board, National Research Council, (2000))	Reviews previous in-service evaluations of the safety effect of guardrail terminals	Suggested by NCHRP 17-18(4). As reviewed by Neuman et al. (2003) Vol 6. Qualitative information added to synthesis.
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Model of safety performance of two-lane rural roads.	Roadside barriers are not explicitly considered. Not added to synthesis
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Guardrails discussed with other roadside features that errant vehicles may strike.	No relevant information. Not added to synthesis.
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))	Analysis of several roadside characteristics on about 100 km of State Route 3 in Washington State using negative binomial models.	Due to uncertainty of models, in the estimation of AMFs, not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Miaou, S. P., "Measuring the Goodness of Fit of Accident Prediction Models." FHWA-RD-96-040, McLean, Va., Federal Highway Administration, (1996))	The study reviews the relationship between roadside accident frequency and hazards exploring the complementary nature of accident and encroachment-based approaches	Roadside barriers were not modeled. Not added to synthesis of this section. Relevant info added to syntheses of other roadside sections.
(Elvik, R., "The Safety Value of Guardrails and Crash Cushions: A Meta-Analysis Of Evidence From Evaluation Studies." Accident Analysis and Prevention, Vol. 27, No. 4, Oxford, N.Y., Pergamon Press, (1995) pp. 523-536.)	Meta-analysis of 32 studies that evaluated the safety effect of guardrails along the edge of the road and impact attenuators	Suggested by NCHRP 17-18(4); reviewed by Hauer (2000); conclusions taken from Elvik (2004) as they have CI indicated. Not added to synthesis.
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))	Overview of impact on safety of various cross-section elements.	No additional information on barriers; not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Summary of safety research of various traffic control and cross-section elements.	No additional quantitative information; not added to synthesis.
(Dawson, R. F. and Oppenlander, J. C., "General Design." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 11, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Reports the relationship between safety and general design features of highways.	Before/after values for guardrail installation from California improvement projects; very limited and outdated information; not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reviews highway safety aspects of cross-section elements.	Some discussion of the merits of median and roadside barriers and guardrails; appears to be superseded by Roadside Design Guide (warrants). Not added to synthesis.

Treatment: Install shoulder guardrails along embankments or changing to softer guardrails

All road types

Elvik and Vaa (2004) performed meta-analyses of studies on guardrails along embankments, including both U.S. and International studies (*8*). The range of traffic volumes and road types were mixed in the study. Details such as the distance to the guardrail were not stated in the source studies.

Elvik and Vaa note that "changing to more pliant guardrails also has a damage-reducing effect, but this is smaller than the effect of setting up guardrails in places where previously there were none" (pg 350) (*8*). Elvik and Vaa also state "guardrails do not have an equally great effect on all types of obstacles… a significant reduction in the severity of injuries sustained in crashes with trees, rock faces and driving off the road in steep slopes. The reduction in injuries is, however, smaller with regard to hitting signposts or ditches" (pg 350) (*8*).

The type of roadside barrier applied can vary from very rigid to less rigid. In order of rigidity, the following generic types of barriers may be considered: (*8*)

- Bridge rail (most rigid)
- Concrete
- Steel
- Wire (least rigid)

Based on the information provided by Elvik and Vaa (2004), the s ideal for these values are based on the 95% confidence interval, and then modified by a method correction factor of 1.8. The resulting indices of effectiveness and standard error values are summarized in Exhibit 3-44.

Exhibit 3-44: Safety effect of guardrails along the roadside (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	New guardrail along embankment	Not reported	Mixed	Run-off-road, fatal	0.56	0.099
Elvik and Vaa, 2004	New guardrail along embankment	Not reported	Mixed	Run-off-road, injury	0.53	0.050
Elvik and Vaa, 2004	New guardrail along embankment	Not reported	Mixed	Run-off-road, all severities	0.93	0.306
Elvik and Vaa, 2004	Changing to softer guardrails	Not reported	Mixed	Run-off-road, fatal	0.59	0.306
Elvik and Vaa, 2004	Changing to softer guardrails	Not reported	Mixed	Run-off-road, injury	0.68	0.099

Treatment: Install median guardrails

Rural two-lane roads

Not applicable.

Rural multi-lane highways; Freeways; Expressways

Elvik and Vaa performed a meta-analysis of the safety effect of median guardrails on divided highways, based on the results of 22 studies (15 U.S., 7 international). The analysis includes some information on the type of guardrail placed in the median (*8*). These values are for all accidents on divided multi-lane roads. Elvik and Vaa state that “median guardrails are seen to prevent nearly all accidents in which vehicles actually cross the median and reduce the severity of accidents greatly” (*8*) (pg 352).

Traffic volume is rarely stated in source studies, but it is reasonable to assume that it is in the range of 20,000 to 60,000 veh/day. Based on the information provided by Elvik and Vaa (2004), the s ideal for these studies was based on the 95% confidence interval, and then modified by a method correction factor of 1.8. The resulting t and s values are summarized in (Exhibit 3-45).

Exhibit 3-45: Safety effect of guardrails and guardrail type in the median of multi-lane divided highways (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Median guardrail	Not reported	Multi-lane divided highways, volume not reported	All types, fatal	0.57	0.099
Elvik and Vaa, 2004	Median guardrail	Not reported	Multi-lane divided highways, volume not reported	All types, injury	0.70	0.059
Elvik and Vaa, 2004	Median guardrail	Not reported	Multi-lane divided highways, volume not reported	All types, all severities	1.24	0.027
Elvik and Vaa, 2004	Install concrete guardrail in median	Not reported	Multi-lane divided highways, volume not reported	All types, injury	1.15	0.356
Elvik and Vaa, 2004	Install steel guardrail in median	Not reported	Multi-lane divided highways, volume not reported	All types, injury	0.65	0.077
Elvik and Vaa, 2004	Install wire (cable) guardrail in median	Not reported	Multi-lane divided highways, volume not reported	All types, injury	0.71	0.113

Hauer (2000) performed a critical review of literature from 1953 to 1997 which studied the use of guardrails as a median barrier (*15*). Based on the studies available, Hauer draws some conclusions regarding median barriers, however no quantitative solution is reached. Only one study had sufficient information to determine a quantitative conclusion, Sacks (1965) studied the safety effect of placing a beam barrier in a 4 ft median on an expressway with ADT 130,000 veh/day or greater. The results of that study are shown in Exhibit 3-46. This study had a known increase in volume, and was rated low (method correction factor of 3).

These results are indicative of the other findings reviewed by Hauer. Hauer states “The basic trade-off is clear. Placing a barrier in the median will largely eliminate the severe cross-median accidents. These are the very accidents that tend to create adverse publicity for the highway agency and are the impetus for public pressure to erect a median barrier. At the same time, the barrier will become the target of crashes that would otherwise not occur. It will cause additional accidents by deflecting vehicles back into the traffic stream. In addition, for narrow medians, the barrier seems to cause increases in speed in the median lane and changes in vehicle placement that reduce the clearance between parallel streams. The net effect of placing a barrier in the median is usually an increase in total accidents; an increase in injury accidents and its effect on the total number of fatal accidents is at present unclear. Traditionally, highway agencies took the position that it is the total accident impact that matters. This position may be eroding under the pressure of adverse publicity” (pg 6.52) (*15*).

Exhibit 3-46: Safety effect of placing beam barrier in 4 ft median on expressway with ADT 130,000 veh/day (15)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Sacks (1965) as cited in Hauer (2000)	Install beam barrier in 4 ft median	Not reported	Expressway, 130,000 veh/day	All types, fatal	0.13	0.414
Sacks (1965) as cited in Hauer (2000)	Install beam barrier in 4 ft median	Not reported	Expressway, 130,000 veh/day	All types, injury	1.18	0.462
Sacks (1965) as cited in Hauer (2000)	Install beam barrier in 4 ft median	Not reported	Expressway, 130,000 veh/day	All types, PDO	1.40	0.344
Sacks (1965) as cited in Hauer (2000)	Install beam barrier in 4 ft median	Not reported	Expressway, 130,000 veh/day	Cross-median, all severities	0.22	0.194

The following points are excerpts from Hauer's review of the literature (*15*):

- For ADT<130,000 veh/day, both the injury and the total accident rate are higher when a median barrier is installed. No attempt has been made to examine the validity of this assertion as a function of median width. Also, fatal and injury accidents were lumped together and this does not allow one to account properly for the larger mortality of cross-median accidents.
- A before/after study by Johnson (1964) shows that the installation of a cable or beam barrier resulted in an increase in total accidents (22% for cable, 32% for beam), increase in injury accidents (18% for cable and 30% for beam) and no change in fatal accidents. This is similar in direction and magnitude to the results summarized in Exhibit 3-46 for injury and PDO accidents.
- A statewide with/without comparison shows that urban freeways with ADT>50,000 and with no barrier have considerably fewer accidents. The same seems to be true for the fatal accident rates but the numbers are too small to tell.
- Whether barrier installation on a freeway is of safety benefit seems to depend on the width of the median. The impression is that in medians up to 36' the barrier was beneficial. For wider medians in the 40-46 foot range it was detrimental. Thus, differentiation by median width is important.
- One must differentiate between median barriers on freeways and non-freeways. On non-freeway projects, the use of a median barrier was harmful.
- The use of a barrier in the conditions where the barrier is now not warranted can be expected to increase the number of accidents, increase the number of injury accidents, and perhaps decrease the number of fatal accidents. The increase in PDO and injury accidents is very consistent. The savings in fatal accidents cannot be confidently estimated because the number in each cell is small.

Also, Hauer notes, "Because little can be said about the impact of median barriers on fatal accidents, many early studies lumped fatal and injury accidents together. In retrospect, this was a mistake. The essence of a median barrier seems to be that in some conditions it may save fatalities whilst increasing injuries and property damage. Therefore the distinction between fatal and non-fatal injury accidents is all-important. By lumping the two these early studies developed powerful prejudices against the use of median barriers" (pg 6.52) (*15*).

Urban and suburban arterials

No studies found.

Treatment: Install wire guardrails between lanes of opposing traffic

Three-lane undivided roads (uncommon in North America)

Elvik and Vaa (2004) reviewed a Swedish study (Carlsson et al., 2000) that evaluated the placement of wire guardrails between the lanes of opposing traffic on undivided three lane highways in Sweden (i.e., two lanes in one direction, one in the other, alternating every few kilometers) (*8*). These kinds of highways may not be very common in North America. Typical traffic volume is 5,000 to 20,000 veh/day. The guardrails are intended to prevent, or reduce the severity of, head-on crashes. Elvik and Vaa found a 100% reduction in fatal crashes (AMF=0.0, s=2.5), a 26% reduction in serious and slight injuries (AMF=0.74, s=0.84), and an increase of 34% of all accidents (fatal, injury and PDO combined) (AMF=1.34, s=0.74) (Exhibit 3-47). The standard errors were calculated based on the number of accidents before and after the treatment, and a method correction factor of 5 (rating of very low) was applied due to the lack of detail reported in the original study, the likely influence of regression-to-mean, and the limitation of only one study performed.

Exhibit 3-47: Safety effect of wire guardrails between opposing lanes of traffic on three-lane undivided roads (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Wire guardrail between lanes of opposing traffic	Not reported	Three lane undivided highway, 5,000 to 20,000 veh/day	All types, fatal	0.00[a]	2.54
Elvik and Vaa, 2004	Wire guardrail between lanes of opposing traffic	Not reported	Three lane undivided highway, 5,000 to 20,000 veh/day	All types, injury	0.74	0.835
Elvik and Vaa, 2004	Wire guardrail between lanes of opposing traffic	Not reported	Three lane undivided highway, 5,000 to 20,000 veh/day	All types, all severities	1.34	0.743

NOTE: (a) AMF for fatal crashes has large standard error

Hunter et al. (2001) developed regression-type models in an attempt to estimate the safety effect of installing three-strand cable median barriers on North Carolina Interstate highway

(*38*). Negative binomial models were used to produce the predicted values, and (over dispersed) Poisson models were used to estimate and test the treatment effects (pg 99). Insufficient information is provided in the TRR article to determine the parameter estimates used in the various models for the various crash types and treatment levels (pre-treatment, transition, post-treatment). This study is not added to the synthesis.

Treatment: Install crash cushions

All road types

Elvik and Vaa (2004) performed a meta-analysis of the safety effect of crash cushions, based on 5 studies (3 U.S., 2 international) (Exhibit 3-48) (*8*). The placement and type of crash cushions, setting, road type, traffic volumes, and other cross-sectional elements of the studied sites are not reported. The standard error is calculated based on the confidence interval of the effect noted by Elvik and Vaa, modified by a factor of 3 due to the uncertainty of the original studies. The results are summarized in Exhibit 3-48.

As noted by Elvik and Vaa "Only two studies that included property damage only accidents are available. One, carried out on an accident black spot, found a strong reduction in the number of accidents. The other, carried out on motorways in Great Britain, found a strong increase in the number of accidents" (pg 353) (*8*). Elvik and Vaa also note that "no studies are available which have evaluated the effect of different types of crash cushions" (pg 353) (*8*).

Exhibit 3-48: Safety effect of new crash cushions at permanent objects (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik, 2004	New crash cushions at permanent objects	Not reported	Not reported	Fixed object, fatal	0.31	0.278
Elvik, 2004	New crash cushions at permanent objects	Not reported	Not reported	Fixed object, injury	0.31	0.098
Elvik, 2004	New crash cushions at permanent objects	Not reported	Not reported	Fixed object, PDO	0.54	0.300

Discussion: Other roadside barrier information

Ray et al. (2002) conducted in-service performance evaluation of the BCT (breakaway cable terminal) and MELT (modified eccentric loader terminal) guardrail terminals in North Carolina, Iowa, and Connecticut. During the 24-month data collection period, the authors collected 169 MELT and BCT cases, including 144 crashes. Ray notes, "in general, these terminals are performing reasonably well. Over 60 percent of the 115 police-reported MELT and BCT crashes resulted in only property damage, and only five involved severe occupant injuries" (pg 115) (*37*). Also "it was shown that about 90 percent of crashes with BCT terminals are minor crashes that results in little property damage, no occupant injury, and are not reported to the police" (pg 115) (*37*). This study does not provide data that can be used to determine an AMF.

AASHTO's Roadside Design Guide contains detailed discussion of guardrail terminal treatments (*26*).

In a previous study, Ray (2000) examined the possible effects of upgrading guardrail terminals (e.g., BCT and MELT) to a newer design (ET-2000) using both police reported and maintenance data in five states(*39*). Ray notes no statistically significant difference in injury severity among three designs, and stresses the need for proper installment. Ray refers to previous studies by Morena and Schroeder (1994) and Agent and Pigman (1991) that also indicate the potential negative safety impact when installed improperly. (*16*)

According to Neuman et al. "Guardrail installations in front of trees will typically reduce crash severity of ROR crashes, although crash frequency may increase in some cases, since a rigid object is placed closer to the roadway than are the trees or other objects being shielded" (*36*). AMFs were not provided. AASHTO's Roadside Design Guide contains further information on barrier installation (*25*).

NCHRP Report 500 Volume 8 contains criteria for the application of barriers or crash cushions to shield utility poles (*30*).

3.1.2.4. Roadside Safety Analysis Program

It is important to implement roadside treatments at sites that will benefit most.(*36*) The above sections have discussed the effects of changes to various individual components of the roadside. Decisions concerning alternative roadside designs with multiple components (e.g., different possible slopes, barrier placement, hardware location, clearzone width, etc.) are often required. As pointed out by Neuman et al. (2003), it is important that the choice of the various roadside strategies that can be implemented at a site be based on optimizing safety benefits. (*36*) The application of the Roadside Safety Analysis Program (RSAP) – a computerized algorithm – predicts roadside crashes based upon roadway, roadside, and traffic descriptors, and examines the benefits and costs of various alternatives. Additional information on the development of RSAP can be found in NCHRP Report 492 "Roadside Safety Analysis Program (RSAP) – Engineer's Manual", which is available at http://trb.org/publications/nchrp/nchrp_rpt_492.pdf.".(*40*)

A description of the RSAP program with a number of proposed applications will be provided in this section. No AMFs will be provided in this section.

Exhibit 3-49: Resources examined for the Roadside Safety Analysis Program

DOCUMENT	DESCRIPTION	COMMENT
(*36*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Lacy, K., and Zegeer, C., "NCHRP Report 500 Volume 3: A Guide for Addressing Collisions with Trees in Hazardous Locations." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2003))	Various strategies aimed to reduce crashes with trees.	Discussion of the benefits of RSAP; added to synthesis.
(*40*) (Mak, K. K. and Sicking, D. L., "NCHRP Report 492: Roadside Safety Analysis Program (RSAP) - Engineer's Manual." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Developed an improved cost-effective analysis procedure to assess roadside safety improvements, the Roadside Safety Analysis Program (RSAP).	Description of RSAP and some applications; added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
("Roadside Design Guide." Washington, D.C., AASHTO, (2002))	Primary resource for roadside element guidance.	Linked to RSAP; not added to synthesis.

Mak et al. (2003) developed a cost-effective analysis procedure to assess roadside safety improvements, culminating in the development of the Roadside Safety Analysis Program (RSAP). Details about the program and its development are documented in "Roadside Safety Analysis Program (RSAP) – Engineer's Manual" for details on program functionality, advantages, and limitations (*40*); and the User's Manual discusses the interface and application. Both manuals and the software are available at http://trb.org/news/blurb_detail.asp?id=1519. The following discussion is adapted from the Engineer's Manual (pg 1-2):

"When determining locations and types of roadside safety devices to be used, the risk of death or injury to road users is weighed against the initial cost of installing and maintaining safety improvements. Sometimes, the choice of safety treatment is not readily apparent, such as for low-volume and/or low-speed roadways. In addition, a performance level must be selected for each situation. Incremental benefit/cost analysis has been widely accepted as the most appropriate method for evaluating safety alternatives. Benefits are measured in terms of expected crash savings or societal benefits associated with a safety improvement; costs are defined as the increase in direct highway agency expenditures associated with the improvement(s). For example, the ROADSIDE program (presented in Appendix A of the 1988 and 1996 editions of AASHTO's Roadside Design Guide) is a benefit/cost analysis program intended for use with site-specific decision-making processes. The Roadside Safety Analysis Program (RSAP) was developed as a new improved cost-effectiveness procedure. RSAP is based on the encroachment probability approach, using a stochastic Monte Carlo simulation technique." (*40*)

RSAP consists of 4 modules, which are described in more detail in "NCHRP Report 492: Roadside Safety Analysis Program (RSAP) – Engineer's Manual" (*40*):

1. Encroachment Probability – uses roadway and traffic information to estimate the expected roadside encroachment frequency along a highway segment. The Cooper encroachment data used by RSAP is also used in the AASHTO Roadside Design Guide (2002).
2. Crash prediction – given that an encroachment has occurred, assesses if the encroachment would result in a crash, using a function for vehicle path (function of encroachment angle, vehicle size, and vehicle orientation), the locations of roadside features, and the probability that the vehicle may return to the roadway or come to a stop before reaching the roadside feature. If a crash is predicted, impact conditions are estimated
3. Severity prediction – for each predicted crash (Module 2) the severity of the crash is estimated using a traditional severity index (SI) approach, similar to that used in the ROADSIDE program (AASHTO Roadside Design Guide 1996), related to impact speed instead of roadway design speed, for each roadside object
4. Benefit/Cost analysis – crash severity estimate is converted to crash cost using values from either the AASHTO Roadside Design Guide or the FHWA comprehensive cost figures based on willingness-to-pay (user's choice)

RSAP is believed to provide much advancement over its predecessors; however, there are also some limitations to the software and prediction modules, such as the age of the encroachment data used in the improved encroachment probability model. In spite of the shortcomings of the current version, RSAP is currently the best tool when considering the safety of highway roadsides.

3.1.2.5. Roadside Hazard Rating

The AASHTO Roadside Design Guide discusses clear zone widths related to speed, traffic volume, and embankment slope. The Roadside Hazard Rating (RHR) system considers the clear zone in conjunction with the roadside slope, roadside surface roughness, recoverability of the roadside, and other elements beyond the clear zone such as barriers or trees (*7*). The Roadside Hazard Rating (RHR) was developed to characterize the accident potential for roadside designs found on two-lane highways (*7*). As the Roadside Hazard Rating increases, from 1 to 7, the crash risk for frequency and/or severity increases. This seven-point categorical scale is discussed in this section.

Exhibit 3-50: Resources examined for the Roadside Hazard Rating

DOCUMENT	DESCRIPTION	COMMENT
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Prediction models developed for two-lane rural roads, incorporating RHR in one of the models.	Added to synthesis.
(*11*) (Zegeer, C. V., Reinfurt, D. W., Hummer, J., Herf, L., and Hunter, W., "Safety Effects of Cross-Section Design for Two-Lane Roads." Transportation Research Record 1195, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 20-32.)	Studied effect on accidents of lane widening, shoulder widening, and shoulder surfacing; used detailed traffic, accident, roadway and roadside data.	Original source of RHR, as cited by Harwood (2000). Added to synthesis.

For the purposes of the accident prediction algorithm for two-lane rural roads (HSM Part III, Chapter 8), roadside design is described by the Roadside Hazard Rating (RHR), a 1 to 7 scale developed by Zegeer et al. (*11*). Quantitative descriptors for the seven RHR levels are summarized in Exhibit 3-51. Exhibit 3-52 to Exhibit 3-58 are photographs illustrating the seven RHR categories.

For the development of the IHSDM, the quality of roadside design was represented by the RHR, as documented in Chapter 8 (HSM Part III) (*7*). Harwood et al. developed the AMF for total accidents based on roadside design directly from their base model for roadway sections (Chapter 8), using the nominal or base value of RHR of 3 (Exhibit 3-54). That is, the AMF is based on the ratio of the accident experience predicted by base model using the actual roadway section in question to the accident experience predicted by the base model using the nominal value of RHR of 3, and can be calculated using Equation 3-6. An estimate of the standard error for this AMF could not be determined.

Equation 3-6: AMF for total accidents on rural two-lane highways based on roadside hazard rating (7)

$$AMF = \frac{\exp(-0.6869 + 0.0668RHR)}{\exp(-0.4865)}$$

Where:

RHR = Roadside hazard rating for the roadway segment

The expert panel that developed this AMF encourages the development of AMFs for specific roadside design elements (*7*). The Roadside Safety Analysis Program (RSAP) was not complete at the time of the development of the rural two-lane model (Chapter 8), and it is recommended that RSAP be used in place of the RHR where the data are available for the road segment in question. (RSAP is discussed in Section 3.1.2.4.) However, the use of RHR data, which can be collected from existing videologs, appears to be a feasible alternative in other applications where detailed roadside inventory data are not available.

Exhibit 3-51: Quantitative descriptors for the seven Roadside Hazard Ratings (7)

Rating	Clear zone width	Sideslope	Roadside
1	Greater than or equal to 30 ft (9 m)	Flatter than 1V:4H; recoverable	N/A
2	Between 20 and 25 ft (6 to 7.5 m)	About 1V:4H; recoverable	N/A
3	About 10 ft (3 m)	About 1V:3H or 1V:4H; marginally recoverable	Rough roadside surface
4	Between 5 and 10 ft (1.5 to 3 m)	About 1V:3H or 1V:4H; marginally forgiving, increased chance of reportable roadside collision	May have guardrail (offset 5 to 6.5 ft, 1.5 to 2 m) May have exposed trees, poles, other objects (offset 10 ft, 3 m)
5	Between 5 and 10 ft (1.5 to 3 m)	About 1V:3H; virtually non-recoverable	May have guardrail (offset 0 to 5 ft, 0 to 1.5 m) May have rigid obstacles or embankment offset 6.5 to 10 ft (2 to 3 m)
6	Less than or equal to 5 ft (1.5 m)	About 1V:2H; non-recoverable	No guardrail Exposed rigid obstacles offset 0 to 6.5 ft (0 to 2 m)
7	Less than or equal to 5 ft (1.5 m)	1V:2H or steeper; non-recoverable with high likelihood of severe injuries from roadside collision	No guardrail Cliff or vertical rock cut

Note: clear zone width, guardrail offset, and object offset are measured from the pavement edgeline

N/A = no description of roadside is provided.

Exhibit 3-52: Typical roadway with Roadside Hazard Rating of 1

Exhibit 3-53: Typical roadway with Roadside Hazard Rating of 2

Exhibit 3-54: Typical roadway with Roadside Hazard Rating of 3

Exhibit 3-55: Typical roadway with Roadside Hazard Rating of 4

Exhibit 3-56: Typical roadway with Roadside Hazard Rating of 5

Exhibit 3-57: Typical roadway with Roadside Hazard Rating of 6

Exhibit 3-58: Typical roadway with Roadside Hazard Rating of 7

3.1.3. Alignment Elements

The following sections describe the elements of the horizontal and vertical alignment of roadway segments and the effect on safety; a future HSM edition will include the effect of combined horizontal and vertical alignments.

A key, but dated comprehensive background reference is “Safety Effectiveness of Highway Design Features: Volume II Alignment” (*41*).

3.1.3.1. Horizontal Alignment

There are several elements of horizontal alignment that may be associated with the safety performance (i.e., accident frequency and severity on the curve) of a horizontal curve, including the internal features (e.g., radius or degree of curve, superelevation, spiral, etc.) and the external features (e.g., density of curves upstream, length of the connecting tangent sections, sight distance, etc.).

The degree of curvature (or curve radius) is defined as the number of degrees of arc subtended by 100 feet of curve length (D). The radius of a curve (R) in meters equals 1748/D. Accident occurrence on a curve is believed to be a function of its degree or, equivalently, of its radius. The radius or degree of curve is a factor ‘internal’ to the curve.

Safety performance of a horizontal curve is also believed to be also a function of the speed, attitudes, and expectations with which road users approach the curve. These are fashioned by what the road users have experienced before reaching the specific curve. Speed choice, driver attitude, and driver expectations may depend on variables such as the length of the preceding tangent or the preceding curve density. These are factors ‘external’ to the curve. *[Adapted from (42).]*

Coverage of this topic would ideally include the safety effects of horizontal alignment and horizontal sight distance, while addressing the safety effects of horizontal design elements such as tangents, curves, superelevation, and spirals, as well as lane and shoulder widening at curves, tangent length between curves, sight distances to entrances on or adjacent to curves, alignment approaches and left-turn movements, and the design for larger vehicles (trucks, buses, etc.). However, because of limitations in the existing knowledge base, it is only effective to address selected aspects in this edition. Specifically, these relate to curve length, curve radius, superelevation, and presence of spirals.

Exhibit 3-59: Resources examined to investigate the safety effect of horizontal alignment on road segments

DOCUMENT	DESCRIPTION	COMMENT
(*43*) (Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	One document from the recent NCHRP Guidebook series; summarizes past research rather than add new knowledge	Added to synthesis
(Harwood, D. W., "Methodology to Predict the Safety Performance of Urban and Suburban Arterials." NCHRP Project 17-26 Interim Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2004))	Interim report summarizes knowledge on safety of design elements for a specific road class	No new results available. Not added to synthesis.
(*3*) (Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Cross-sectional models for a specific road class using HSIS data	Added to synthesis
(Kockelman, K., Lave, C., and Charles River Associates Inc., "Safety Impacts and Other Implications of Raised Speed Limits on High-Speed Roads." NCHRP Project 17-23 Interim Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2003))	On going research. No products of value available	Not added to synthesis
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	One document from the recent NCHRP Guidebook series; summarizes past research rather than add new knowledge	Not added to synthesis – material not relevant or covered elsewhere
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Summarizes AMF knowledge for mainly traffic engineering/operations measures	Not added to synthesis – material not relevant or covered elsewhere
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Ross-sectional analysis of a database in one State -- deemed likely to be of little value	Not added to synthesis
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Provides expert panel AMFs for several horizontal alignment variables	Added to synthesis
(*42*) (Hauer, E., "Safety of Horizontal Curves." (2000))	Synthesizes AMF knowledge fro several horizontal alignment variables	Added to synthesis
(Storm, R., "Pavement Markings and Incident Reduction." Ames, Iowa, 2000 MTC Transportation Scholars Conference, (2000) pp. 152-162.)	Unclear why this is of relevance so it was deemed irrelevant on the basis of the title alone	Not added to synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Hanley, K. E., Gibby, A. R., and Ferrara, T. C., "Analysis of Accident Reduction Factors on California State Highways." Transportation Research Record, No. 1717, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 37-45.)	Provides some AMFs but none of particular relevance – mostly combination measures	Not added to synthesis
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Not reviewed. Likely to be covered in Harwood et al. 2000	Not added to synthesis
(Potts, I. B., Harwood, D. W., and Bauer, K. M., "Effect Of Preceding Tangent Length On Safety For Horizontal Curves." Mainz, Germany, 2nd International Symposium on Highway Geometric Design, (2000) pp. 279-287.)	Cross-sectional analysis of HSIS data for two-lane rural roads in Washington	Not added to synthesis
(Gibreel, G. M, Easa, S. M, Hassan, Y., and El-Dimeery, I. A., "State of the Art Review of Highway Geometric Design Consistency." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1999) pp. 305-313.)	Knowledge on consistency that is not relevant to the 1st HSM edition	Not added to synthesis
(Preston, H. and Schoenecker, T., "Potential Safety Effects of Dynamic Signing at Rural Horizontal Curves." MN/RC-2000-14, St. Paul, Minnesota Department of Transportation, (1999))	Addresses an irrelevant topic – so not reviewed	Not added to synthesis
(Hassan, Y. and Easa, S. M., "Design Considerations of Sight Distance Red Zones on Crest Curves." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1998) pp. 343-351.)	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Lamm, R. and Heger, R., "Recommendations Relevant to International Design Standards for Improving Existing (Old) Alinements Based on Speed and Safety Related Research." Toronto, Ontario, Canada, International Road Federation 13th World Meeting, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Lamm, R., Heger, R., and Eberhard, O., "Operating Speed and Relation Design Backgrounds: Important Issues to be Regarded in Modern Highway Alignment Design." Toronto, Ontario, Canada, International Road Federation 13th World Meeting, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Fambro, D. B., Nowlin, R. L., Warren, S. P., Lienau, K. A., Mounce, J. M., Bligh, R. P., Mak, K. K., and Ross, H. E., "Geometric Design Guidelines for Suburban High-Speed Curb and Gutter Roadways." FHWA/TX-95/1347-1F, College Station, Texas A&M University, (1995))	Does not provide relevant AMF information so not reviewed	Not added to synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V., Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume II - Alignment." FHWA-RD-91-045, Washington, D.C., Federal Highway Administration, (1992))	Comprehensive FHWA project report that contains horizontal alignment AMF information covered in Zegeer, Stewart et al. 1992)	Not added to synthesis
(*44*) (Zegeer, C. V., Stewart, J. R., Council, F. M., Reinfurt, D. W., and Hamilton, E., "Safety Effects of Geometric Improvements on Horizontal Curves." Transportation Research Record 1356, Washington, D.C., Transportation Research Board, National Research Council, (1992))	Provides AMH for several horizontal alignment elements based on cross-sectional regression models	Added to synthesis
(*45*) (Zegeer, C. V., Stewart, R., Reinfurt, D. W., Council, F. M., Neuman, T. R., Hamilton, E., Miller, T., and Hunter, W., "Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves." FHWA-R0-90-021, Federal Highway Administration, (1991))	Superceded by AMF information covered in Zegeer, Stewart et al. 1992)	Not added to synthesis
(Zegeer, C. V., Reinfurt, D., Neuman, T. R., Stewart, R., and Council, F. M., "Safety Improvements on Horizontal Curves for Two-Lane Rural Roads - Informational Guide." FHWA-RD-90-074, McLean, Va., Federal Highway Administration, (1990))	Superceded by AMF information covered in Zegeer, Stewart et al. 1992)	Not added to synthesis
(Agent, K. R. and Creasey, F. T., "Delineation of Horizontal Curves." UKTRP-86-4, Frankfort, Ky., Kentucky Transportation Cabinet, (1986))	Dated and likely irrelevant	Not added to synthesis
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Dated and likely irrelevant. Studies are likely covered in Hauer (2000)	Not added to synthesis
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Dated and likely irrelevant. Studies are likely covered in Hauer (2000)	Not added to synthesis

Treatment: Flatten horizontal curves

Rural two-lane roads

Research on rural two-lane highways for Chapter 8 in HSM Part III (*7*) identified the relationship between horizontal alignment and safety. In the base model, curves in roadway segments were included based on their degree of curvature with a tangent roadway section as the nominal condition. This was modified using two Accident Modification Functions. The first Accident Modification Function accounts for the length and radius of curves, and the presence or absence of spiral transitions. Generally, accident risk decreases with longer radii, longer lengths of horizontal curves, and the presence of spirals.

In Harwood et al. (2000), the AMF for horizontal curves has been determined from the regression model developed by Zegeer et al. (1992) that included the safety effects of length of horizontal curve, degree of horizontal curve, and presence or absence of spiral transition curves (*7*). The AMF for horizontal curvature is in the form of an Accident Modification Function rather than an Accident Modification Factor. The AMF for length, radius, and presence or absence of spiral transitions for total accidents on horizontal curves is shown in Equation 3-7.

Equation 3-7: AMF for length, radius, and presence or absence of spiral transitions on horizontal curves on two-lane rural roads (7)

$$AMF = 1.55L_c + (80.2/R) - 0.012S] / 1.55L_c$$

Where:

L_c = Length of horizontal curve (mi);

R = Radius of curvature (ft); and

S = 1 if spiral transition curve is present

0 if spiral transition curve is not present

In applying the Accident Modification Functions for curves with spiral transitions, the length variable (L_c) should represent the length of the circular portion of the curve. P-values of 0.0001 for length and radius, and 0.148 for the spiral presence variable were reported in Zegeer et al. (1992) (as cited in (*7*)). Chapter 8 of the HSM contains further discussion of the models developed for two-lane rural roads.

Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Hauer et al. (2004) calibrated models to data from Washington State in order to predict the non-intersection accident frequency of urban four-lane undivided roads (*3*). Separate models were estimated for 'off-the-road' and 'on-the-road' Property Damage Only (PDO), Injury, and Total accidents: a total of six models. The data came from the files maintained by the Highway Safety Information System (HSIS) entailing 121.95 miles of road over the four years 1993 to 1996 during which there were 895 off-the-road and 5288 on-the-road accidents, split approximately equally between PDO and Injury accidents.

For off-the-road accidents, the effect of the degree of horizontal curvature was captured by the multiplier exp (β× Degree of Curve) where β took values of 0.041, 0.056 and 0.051, respectively, for PDO, injury and total accidents. The AMFs implied are, respectively, 1.04, 1.06, and 1.05 for PDO, injury, and total accidents for an increase of one degree of curvature, summarized in Exhibit 3-60. Hauer estimated standard errors of each parameter, and a method correction factor of 1.5 was applied to the estimate the standard error.

Exhibit 3-60: AMFs for off-the-road accidents for one degree increase in horizontal curvature on urban and suburban arterials (3)

Off-the-road accident severity	AMF	S
PDO	1.04	0.01
Injury+Fatal	1.06	0.01
Total	1.05	0.01

For on-the-road accidents, the relationship appeared to be more complex since the number of on-the-road accidents/mile-year for horizontal curves was considerably and unexpectedly lower than that for straight miles of road. Since the on-the-road accidents dominate for this roadway class, Hauer concluded that the role of horizontal curvature in road safety for four-lane undivided arterials may need rethinking.

Treatment: Improve superelevation of horizontal curve

Rural two-lane roads

The AMF for superelevation provided by Harwood et al. (2000) is based on the superelevation deficiency of a horizontal curve (i.e., the difference between the actual superelevation and the superelevation required by AASHTO policy) (*7*). When the actual superelevation meets or exceeds that required by AASHTO policy, the value of the superelevation AMF is 1.00. The expert panel made a judgment that there would be no effect of superelevation deficiency on safety until the superelevation deficiency exceeds 0.01. AMFs are given in Exhibit 3-61. Insufficient information was reported for the derivation of standard errors.

Selected AMFs based on these equations are presented in Exhibit 3-62 below. All AMFs in Harwood et al. apply only to total roadway segment accidents for roadway segments located on horizontal curves of two-lane roads. Chapter 8 of the HSM contains further discussion of the models developed for two-lane rural roads.

Exhibit 3-61: AMFs for superelevation deficiency (SD) of horizontal curves on two-lane rural roads (7)

Superelevation deficiency (SD)	AMF
$SD < 0.01$	$= 1.00$
$0.01 \leq SD < 0.02$	$= 1.00 + 6 (SD - 0.01)$
$SD > 0.02$	$= 1.06 + 3 (SD - 0.02)$

Exhibit 3-62: AMFs for superelevation deficiency (SD) of horizontal curves on two-lane rural roads (7)

Superelevation deficiency (SD)	AMF
0.01	1.00
0.02	1.06
0.03	1.09
0.04	1.12
0.05	1.15

Treatment: Increase tangent length in advance of curve

All road types

Hauer (2000) postulates that accident occurrence on a curve is believed to be a function of the speed, attitudes and expectations with which road users approach the curve which, in turn, may depend on variables such as 'the length of the preceding tangent' or the 'preceding curve density' (*42*). After reviewing a number of studies, Hauer (2000) concludes that the weight of empirical evidence is that when a long tangent is followed by a sharp curve, the number of accidents is elevated. The AMF in Equation 3-8 was derived by Hauer from data and equations in Matthew and Barnes (1988)[1] and was seen by Hauer to capture this phenomenon for curves with R<500 m and T<1200 m. This AMF is based on data from New Zealand State Highway #1; the characteristics of this highway are not reported.

Equation 3-8: AMF for a tangent section followed by a sharp curve (42)

$$AMF = \exp[-(6.2\times10^{-4} - 1.2\times10^{-6}R)\times(1200-T)]$$

Where R is the radius in meters

T is the length of the tangent in meters

Thus, for example, if the 250 m radius horizontal curve is preceded by a 400 m tangent it will have 0.77×number of accidents of a 250 m radius curve preceded by a very long tangent (longer than 1200 m), as summarized in Exhibit 3-63. In the absence of specific information, and based on logical considerations, it can be presumed that this AMF information can be applied with caution to all crash severities for all impact types combined and to accidents occurring on the curve.

Exhibit 3-63: AMFs for short tangents (T) followed by a sharp curve (R = radius) (42)

	T[m]														
R[m]	50	100	150	200	250	300	400	500	600	700	800	900	1000	1100	1200
50	0.53	0.54	0.56	0.57	0.59	0.60	0.64	0.68	0.71	0.76	0.80	0.85	0.89	0.95	1.00
100	0.56	0.58	0.59	0.61	0.62	0.64	0.67	0.70	0.74	0.78	0.82	0.86	0.90	0.95	1.00
150	0.60	0.62	0.63	0.64	0.66	0.67	0.70	0.73	0.77	0.80	0.84	0.88	0.92	0.96	1.00
200	0.65	0.66	0.67	0.68	0.70	0.71	0.74	0.77	0.80	0.83	0.86	0.89	0.93	0.96	1.00
250	0.69	0.70	0.71	0.73	0.74	0.75	0.77	0.80	0.83	0.85	0.88	0.91	0.94	0.97	1.00
300	0.74	0.75	0.76	0.77	0.78	0.79	0.81	0.83	0.86	0.88	0.90	0.92	0.95	0.97	1.00
350	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.87	0.89	0.90	0.92	0.94	0.96	0.98	1.00
400	0.85	0.86	0.86	0.87	0.88	0.88	0.89	0.91	0.92	0.93	0.95	0.96	0.97	0.99	1.00
450	0.91	0.92	0.92	0.92	0.93	0.93	0.94	0.95	0.95	0.96	0.97	0.98	0.98	0.99	1.00
500	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00

1 Matthews, L.R., and Barnes, J.W., (1988). Relation between road environment and curve accidents. Proceedings, 14 ARRB Conference, Part 4, pp. 105-120.

Discussion: Effect of degree (or radius) of curve

Hauer (2000) summarized a large number of studies (*42*) and concluded that "most research showed that the relationship between the curve accident rate 'r' and degree of curve D is of the linear form" shown in Equation 3-9.

Equation 3-9: Linear relationship between accident rate and degree of curvature (42)

$$r = r_o + \alpha D$$

Where *ro* is the accident rate on tangents (accidents / million-vehicle-miles).

An alternative model form was developed by Zegeer et al. (1991, 1992) (*44,45*) from a database of 10,900 horizontal curves in Washington State. The model shown as Equation 3-10 was adopted. However, further research on the effect of degree (or radius) of curve is needed to determine a definitive AMF.

Equation 3-10: Relationship between accidents, degree of curve, presence of spirals, volume and roadway width (44,45)

$$A = (1.552L + 0.014D - 0.012S) \times V \times 0.978W\text{-}30$$

Where A is the number of accidents/year

L is length of curve in miles

D is degree of curve

S = 1 if spirals exist and 0 otherwise

V is volume of vehicles/year in millions (both directions)

W is 'roadway width in feet' - the total width of lanes +shoulders

Hauer finds that if the functional form in Equation 3-10 is correct, when a curve of degree D_1 is replaced by a less sharp curve of degree D_2 then the annual reduction in accidents is shown in Equation 3-11.

Equation 3-11: Annual accident savings due to curve flattening

$$\text{Annual Accident Savings} = V\,[r_o\,(1/D_1 - 1/D_2)\,(2\tan(I/2) - I) + 0.014(D_2 - D_1)]$$

Where V is volume of vehicles/year in millions (both directions)

r_o is the accident rate on a straight section of that road

I is the deflection angle

If, on the other hand, the model form in Equation 3-9 is correct, then the last term in Equation 3-11 needs to be omitted.

Discussion: Relationships between safety and stopping sight distance (SSD), and preview sight distance (PVSD)

Torbic et al.'s review for the NCHRP 500 Series Guidebook concludes: "It is difficult to determine the expected safety benefits of improving the sight distance at a horizontal curve when the available sight distance is slightly less than the minimum stopping sight distance. The accident statistics do not provide a sufficient amount of information to determine the expected safety benefits. There is some indication from research (see NCHRP Report 400) that improving locations with substantial sight distance restrictions offers safety benefits" (*43*).

3.1.3.2. Vertical Alignment

The vertical alignment (also referred to as grade, gradient, or slope) of a road is likely to affect safety by various mechanisms. Vehicles tend to slow down going upgrade and speed up going downgrade. Speed is known to affect accident severity. The more severe an accident, the more likely it is to be reported to the police and thus to enter the official statistics. It follows that the number of reported accidents depends on speed and thereby on grade. In addition, it is possible that the frequency of accident occurrence increases when the diversity of speed increases. Since road grade affects the diversity of speeds, it may affect accident frequency. Also, grade affects braking distance. This too may have an effect on accident frequency and severity. Grade also influences the rate at which water drains from the pavement surface and thus may have an effect on safety.

The existence of several diverse mechanisms working together means that the final outcome (accidents) may be a complex superposition of many processes. For some processes (e.g., drainage) the distinction between upgrade and downgrade is immaterial. For other processes (e.g., the change in average speed) the distinction between up and down-grade is crucial. The length over which the grade prevails may have a substantial influence on the safety effect of a grade. While speed may be unaffected by a short downgrade it may be significantly affected by a longer one. Yet, in the various studies to date there may has been little distinction in between a 1/2 mile and a 5 mile downgrade. Furthermore, while the grade on a crest curve or in a sag curve may be similar, the speed distribution at the two locations is likely to be very different. In short, the safety effect of grade can be understood only in the context of the road profile and its influence on the speed distribution profile. *[Adapted from Hauer (2001) (46).]*

This section would ideally include information on the safety effect of roadway segments due to changes in vertical alignment. This could include the effect of modifying grades along sag and crest vertical curves. Nighttime sight distances and presence of driveways along vertical curves are some of the elements that may be covered in future versions of this section. At this time, there is sufficient information in the literature to discuss the safety effect of reducing vertical grade of roadway segments.

Exhibit 3-64: Resources examined to investigate the safety effect of vertical grade on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Examined effect of grade and vertical curves but results were inconclusive or unreliable	Not added to synthesis
(*47*) (Miaou, S.P., "Estimating Roadside Encroachment Rates with the Combined Strengths of Accident- and Encroachment-Based Approaches, Final Report" FHWA-RD-01-124, Federal Highway Administration, Washington, D.C. (2001))	NB regression models for *single-vehicle-run-off-road* on two-lane rural road segments in Washington and Minnesota	Added to synthesis.
(*46*) (Hauer, E., "Road Grade and Safety." (2001))	Reviewed a number of early studies on the safety effect of road grade	Used to develop AMFs in Harwood et al. (2000). Added to synthesis.
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Cross-sectional analysis of design attributes and crash data in Oregon.	Not added to synthesis
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Development of safety effect estimates for two-lane rural roads.	Added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Review of past literature – deemed to be irrelevant	Not added to synthesis
(Gibreel, G. M, Easa, S. M, Hassan, Y., and El-Dimeery, I. A., "State of the Art Review of Highway Geometric Design Consistency." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1999) pp. 305-313.)	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Hassan, Y. and Easa, S. M., "Design Considerations of Sight Distance Red Zones on Crest Curves." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1998) pp. 343-351.)	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(*48*) (Miaou, S.P. "Vertical Grade Analysis Summary "Center for Transportation Analysis,Oak Ridge National Laboratory, (1998))	Analysis of two-lane highway grades in Utah	Added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Lamm, R., Heger, R., and Eberhard, O., "Operating Speed and Relation Design Backgrounds: Important Issues to be Regarded in Modern Highway Alignment Design." Toronto, Ontario, Canada, International Road Federation 13th World Meeting, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Lamm, R. and Heger, R., "Recommendations Relevant to International Design Standards for Improving Existing (Old) Alinements Based on Speed and Safety Related Research." Toronto, Ontario, Canada, International Road Federation 13th World Meeting, (1997))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(*49*) Miaou, S.P. "Development of Adjustment Factors for Single Vehicle Run-off-the-road Accident Rates by Horizontal Curvature and Vertical Grade" Center for Transportation Analysis,Oak Ridge National Laboratory, (1995)	Cross-sectional study of multi-lane roads in Utah.	Added to synthesis.
(Curren, J. E., "NCHRP Report 369: Use of Shoulders and Narrow Lanes to Increase Freeway Capacity." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Fambro, D. B., Nowlin, R. L., Warren, S. P., Lienau, K. A., Mounce, J. M., Bligh, R. P., Mak, K. K., and Ross, H. E., "Geometric Design Guidelines for Suburban High-Speed Curb and Gutter Roadways." FHWA/TX-95/1347-1F, College Station, Texas A&M University, (1995))	Does not provide relevant AMF information so not reviewed	Not added to synthesis
(Zegeer, C. V., Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume II - Alignment." FHWA-RD-91-045, Washington, D.C., Federal Highway Administration, (1992))	Likely superceded by, and considered in reviews by Hauer (2001) and Harwood et al. 2000	Not added to synthesis
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Dated. Studies are likely covered in other reviews	Not added to synthesis.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Dated and likely irrelevant. Studies are likely covered in other reviews	Not added to synthesis

Hauer (2001) reviewed a number of early studies of the safety effects of modifying grades that do not seem to provide useful AMF information in that they are either dated or are methodologically flawed. Therefore, these studies are not reviewed here, but are summarized in Exhibit 3-65, which has been extracted from Hauer (*46*).

Exhibit 3-65: List of studies reviewed by Hauer (Table 7.18 from (46))

Year/ Ref.	Method	Size	Accident modification functions	Acc. type	Conf. rating	Conditions	Comments
Raff 1953	C/S Uni and bi-variate	15 states	"on tangent highway sections there does not appear to be any relation between grade and accident rates.	all	0.5	Sample from 15 states	Pooled data does not allow any inferences
Bitzel, 1956	C/S Uni-variate	German Freeways	0%-2% 2%-4% 4%-6% 6%-8% 1.00 1.45 4.08 4.52	all	0.5		Out of line with other results. Most likely due to confounding with other variables
Mullins & Keese, 1961	C/S collision diagrams	54 miles of freeway, 10,000 accidents	Accidents/MVM seem to vary as speed varies: diminish from sag towards crest and then increase towards sag.	All	1.5	Texas cities	
Hillier & Wardrop, 1966	C/S along one road	55 miles of motor-way	If curve B then 0% 0.5% 1% 1.5% 2.0% 1.00 1.02 1.09 1.19 1.39 AMF=(1-0.068*%grade²)⁻¹	Injury	2	London to Birmingham Straight sections	Differentiates between upgrade and downgrade lanes
Crosstown Associates 1968	C/S Along freeway	Chicago Expressway	Accidents/MVM Upgrade 1.87 +/- 0.5% 1.10 Downgrade 2.49	All	1		
Vostrex & Lundy, 1964	C/S accident rate		Accidents/MVM 4-5% trucks 11% trucks Level 0.84 1.17 Up grade 0.71 1.51 Down grade 1.07 1.29	All	1.5	Straight freeway sections in California	When proportion of truck is large, upgrade accident rate grows
Cirillo 1969	C/S Multivariate regression	Interstate system	Grade was significant in one of two models. Annual accidents increase by 0.01 for each 1000 ADT for each 1% of grade	all	1		
Dunlap et al., 1978	Ohio and Pennsylvania turnpikes		Accident rate increases with downrade and remains constant with upgrade. AMF is about 1.10/%grade	all	1.5		
Hedman, 1990	C/S	Swedish roads.	Study by Brude at al. AMF= 1.044/%grade	?	?		
Li et al. 1994	C/S Multi-variate	163 sections 560 km	AMF($\Delta_{\%grade}$)=1+0.136 $\Delta_{\%grade}$/ √Accid/km Ex.: Increase of grade from 2% to 3% when 0.6 accid/km, AMF=1+0.136/.0=1.23	Fat+InjS EVD*	2		Model equation includes ADT in additive form. This is illogical.
Miaou 1995	C/S Multi-variate	11539 road sections 1985-92 Utah 6680 SV.	0.919±0.009 for 1% — All roads 0.960±0.015 for 1% — Speed limit=55 mph 0.892±0.013 for 1% — Speed limit<55 mph	Single veh.. off-the road	2	mainly rural two-lane but including HPMS 2,6,7,8,9 Non-intersection accident	Lane width is not included in variables. Section length is variable with negative coefficient

Treatment: Reduce vertical grade of roadway segment

Rural two-lane roads

The latest AMF information for road grade is in Harwood et al. (2000) and is intended for use in IHSDM and in the HSM two-lane rural highway methodology (Chapter 8) (*7*). In view of the latter context, the relevant paragraphs from this source are reproduced below almost verbatim. Chapter 8 in Part III contains more details of the models developed.

The nominal or base condition for grade is a level roadway (0% grade). Exhibit 3-66 presents the accident modification factor for grades based on an analysis of two-lane highway grades in Utah conducted by Miaou(*48*). This analysis considered accident and geometric data for approximately 2,500 mi (4,000 km) of two-lane roads with 55 mph (88.5 km/h) speed limits, 12 ft (3.6 m) lanes, and tangent alignment. Two analysis approaches were used: univariate analysis using smoothing techniques, and negative binomial regression modeling. Both methods estimated the effect of vertical grade on accidents as approximately a 1.6 percent increase in accidents per one percent increase in grade. However, both studies found this effect to be not statistically significant.

Despite the lack of statistical significance of the results, a decision was reached by the expert panel charged with deriving the rural two-lane road AMFs to use the observed effect as the basis for an AMF because the result appeared reasonable to the expert panel and because no more reliable results are available. Exhibit 3-66 presents AMFs for grade based on the observed 1.6% increase in accidents per 1% increase in grade. The AMFs in this table are applied to each individual grade section on the roadway being evaluated without respect to the sign of the grade (i.e., upgrade or downgrade). The sign of the grade is irrelevant because each grade on a two-lane highway is an upgrade for one direction of travel and a downgrade for the other. The grade factors are applied to the entire grade from one point of vertical intersectional (PVI) to the next (i.e., there is no special account taken of vertical curves). The AMFs in Exhibit 3-66 apply to total roadway segment accidents. For example, increasing the roadway grade by 2% means an increase in total roadway crashes of 3%.

Exhibit 3-66: Accident Modification Factors for all accidents for Increased Grade of Two-Lane Rural Roadway Sections (7)

Grade (%)				
0	**2**	**4**	**6**	**8**
1.00	1.03	1.07	1.10	1.14

In assessing the relevance of these AMFs, it should be noted that standard errors, though said to be large by Harwood et al., are not available. The following studies were reviewed to determine the appropriateness of the values recommended by Harwood et al.:

- Hedman (1990) (p. 231) as referred to in the table from Hauer (2001) mentions a study by Brüde et al. (1980) that found for Swedish roads that "Grades of 2.5% and 4% increase accidents by 10% and 20% respectively, compared to near horizontal roads" (*46*). Using an exponential form to estimate the index of effectiveness:
  - if $x^{2.5} = 1.10$; then x = 1.038
  - if $x^4 = 1.20$; then x = 1.046
    These results point to an AMF of about 1.044 which seems to support the value of 1.6%(or an AMF of 1.016) increase in accidents per 1% increase in grade noted by the expert panel in Harwood et al. (2000).

- Hauer also cites Li et al. (1994) who, using data for 560 km of the British Columbia provincial primary two-lane highway system calibrated a multivariate model for fatal+injury accidents in which grade is one of the variables (*46*). Based on their model, a change of 1% in grade results in a change of approximately 10% in accident frequency, which is somewhat higher than the 1.6% change noted by the expert panel in Harwood et al. (2000) (Exhibit 3-66)
- Hauer also cites earlier work by Miaou (1995) who used data from 11,539 road sections and 6,680 *single-vehicle-run-off-road* accidents to imply an AMF that is such that decreasing the grade by 1% diminishes the number of accidents by 8.1% (*46*). Again, this is somewhat higher than the 1.6% value noted by the expert panel in Harwood et al. (2000) (Exhibit 3-66)
- Miaou (2001), subsequent to his earlier work, constructed negative binomial regression models for *single-vehicle-run-off-road* on two-lane rural road segments in Washington (680 segments) and Minnesota (608 segments) (*47*). Only road segments with average annual daily traffic volumes less than 12,000 and with all horizontal curvatures within a segment less than 30 degrees were selected. The AMF for a 1% increase in grade in Washington was 1.016 (95% C.I. from 0.99 to 1.05) and for Minnesota 1.25 (95% C.I. from 1.19 to 1.31).

Based on the vertical grade analysis completed by Miaou in 1998 for rural two-lane roads with a posted speed limit of 55 mph, lane width of 12 ft and horizontal curvature of 0 degrees, increasing vertical grade by 1% has an AMF of 1.016 for all crashes.(*48*) A standard error for this AMF could not be determined, but this value is adopted in the IHSDM software.

Returning to Miaou's work from 1995 and 1998 provides additional insight. Based on the negative binomial models developed in 1995 for rural two-lane roads, with no median and either surfaced or stabilized shoulders, and a posted speed limit of 55 mph indicates an AMF of 1.041 for a 1% increase in vertical grade with an estimated standard error of about 0.016.(*49*) This AMF and standard error are for single-vehicle run-off-road crashes only, and were derived by the author using on a log-normal assumption. Applying a method correction factor of 1.5 (medium high) results in a standard error of 0.024.

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Studies for other than two-lane roads are few, dated, and inconsistent. Thus no credible AMF can be said to exist for these, a view supported by an expert panel drawn to look at AMFs for 4-lane roads subsequent to the two-lane road panel. The two-lane rural road AMFs for vertical grade may not be applicable to other road types. The expert panel recommended that an analysis of grade effects on multi-lane highways similar to that performed for two-lane highways by Miaou (1998) be conducted (*7*).

3.1.3.3. Combination Horizontal and Vertical Alignment [Future Edition]

In future editions of the HSM, this section will discuss the safety impact of combined horizontal and vertical alignment. This section may also discuss design consistency, and speed profile issues. Potential resources are listed in Exhibit 3-67.

Exhibit 3-67: Potential resources for the relationship between combined horizontal and vertical alignment and safety

DOCUMENT
(Hauer, E., "Road Grade and Safety." (2001))
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))
(Hassan, Y. and Easa, S. M., "Design Considerations of Sight Distance Red Zones on Crest Curves." Journal of Transportation Engineering, Vol. 124, No. 4, New York, N.Y., American Society of Civil Engineers, (1998) pp. 343-351.)
(Zegeer, C. V., Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume II - Alignment." FHWA-RD-91-045, Washington, D.C., Federal Highway Administration, (1992))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))

3.2. Safety Effects of Roadway Segment Traffic Control and Operational Elements

The following sections contain information on the safety effects of traffic control devices and operational elements such as signs, pavement markings and markers, rumble strips, traffic calming and speed zoning, on roadway segments. Traffic control devices for intersections are discussed in Chapter 4.

The “Manual on Uniform Traffic Control Devices” contains details on the implementation of design of traffic control devices, and can be found at http://mutcd.fhwa.dot.gov/ (*50*).

3.2.1. Signs

Traffic signs are typically classified as one of three categories: regulatory signs; warning signs; and guide signs. As defined in the Manual on Uniform Traffic Control Devices (MUTCD) (*50*), regulatory signs provide notice of traffic laws or regulations, warning signs give notice of a situation that might not be readily apparent, and guide signs show route designations, destinations, directions, distances, services, points of interest, and other geographical, recreational or cultural information. While the MUTCD provides the standards, as well as guidance and options necessary for signing within the right-of-way of all types of highways open to public travel, many agencies supplement the information contained in the MUTCD with their own guidelines and standards. It should be noted that the MUTCD does not specify the conditions (traffic, road geometry, etc.) under which the signs are to be used.

This section examines the safety effects of signage along roadway segments and excludes any consideration for signs at intersections.

Chapter 4 contains additional discussion on the safety impacts of signage at intersections and roundabouts. Given that a large number of studies that investigate the safety impacts of signs on urban road segments are related to pedestrian crosswalks, Section 3.3 Pedestrian and Bicyclist Safety contains relevant information. Chapter 6 contains information on signage within work zones.

Exhibit 3-68: Resources examined to investigate the safety effect of Signs on Roadway Segments

DOCUMENT	DESCRIPTION	COMMENT
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics	Added to synthesis. Accident reduction values found for advance curve warning and recommended speed signs.
("Manual on Uniform Traffic Control Devices for Streets and Highways." Washington, D.C., Federal Highway Administration, (2003))	The national standard for all traffic control devices installed on any street, highway, or bicycle trail open to public travel.	No safety information provided. Used as reference for definitions and guidelines on usage of signs. Not added to synthesis.
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Strategy 12.1 E2 proposes the installation of interactive truck rollover signing to reduce rollover crashes on ramps. However, no safety effect information is given.	No safety information provided – not added to synthesis.
(*51*) (Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Study reviews and brings together the best available evidence on the safety impact of traffic operations. All the studies reviewed report on crash occurrence, severity or proven crash surrogates	Added to synthesis. Several studies reviewed offer quantitative data.
(Harmelink, M., Edwards, R., Lovicsek, M., Quinton, M., Smiley, A., Bahar, G., McGowan, G., and Pacheco-Phillips, K., "Ontario Traffic Manual Book 1A: Illustrated Sign and Signal Display Index." Toronto, Ontario, Canada, Queen's Printer for Ontario, (2001))	Illustrated guide to standard traffic signs	No safety information provided. Used as reference for definitions and guidelines on usage of signs. Not added to synthesis.
(Van Houten, R., Malenfant, J. E., and McCusker, D., "Advance Yield Markings: Reducing Motor Vehicle-Pedestrian Conflicts at Multilane Crosswalks with Uncontrolled Approach." Transportation Research Record, No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 69-74.)	Evaluated the effect of advance yield markings and a symbol sign on pedestrian safety at intersections; used conflicts, pedestrian and motorist behavior as surrogate.	Not added to synthesis since more relevant to Pedestrian and Bicyclist Safety at Intersections).
(*28*) (Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways through a review of previous studies.	Added to synthesis. Some anecdotal evidence of speed reductions resulting from signs at horizontal curves but no quantitative information provided about safety impacts.

DOCUMENT	DESCRIPTION	COMMENT
(*52*) (Tribbet, L., McGowen, P., and Mounce, J., "An Evaluation of Dynamic Curve Warning Systems in the Sacramento River Canyon." Sacramento, California Department of Transportation, (2000))	Investigated the safety effectiveness of dynamic curve warning systems (changeable message signs)	Added to synthesis. No AMFs presented but there is sufficient quantitative data to calculate t and s values.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Reviews existing research and attempts to provide guidelines on highway engineering improvements that would help older drivers and pedestrians.	Not added to synthesis. No discussion on safety impacts of signs.
(McGee, H.W., Strickland, R.R., "An Automatic Warning System to Prevent Truck Rollover on Curved Ramps" Public Roads, Vol. 57· No. 4 Washington, D.C., Federal Highway Administration, (1984))	Assessed the details of creating and implementing an automated warning system.	Not added to synthesis. Insufficient information on crash reductions due to sign installation.
(*53*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis study reviewing 17 safety research areas	Added to synthesis. Qualitative evidence of speed reduction at horizontal curves due to skid warning signs. No other information about safety impacts.
(Dawson, R. F. and Oppenlander, J. C., "General Design." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 11, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Reference discusses the relationship between safety and general design features of highways mainly in terms of accident rates and costs	Not added to synthesis. Quantitative information on crash reductions due to signs but insufficient information about specific type of treatment, type of facility etc. to assign t and s values.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Reference discusses the relationship between safety and horizontal and vertical alignment	Not added to synthesis. Some qualitative about crash and speed reductions resulting from the implementation of signs at horizontal curves but insufficient information to calculate t and s values

Based on review of the identified references, it is apparent that there are very few studies that explicitly investigate the safety impacts of signage. Where available, the effectiveness of a variety of regulatory and warning signs has been quantified for both urban and rural roadways. Given the limited information available from the references reviewed, it was not possible at times to discern the specific types of roadways these safety effectiveness indices are applicable. In addition, volume ranges were not always available.

Treatment: Install signs to conform to MUTCD

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Urban local streets

Elvik and Vaa reviewed a study by Lyles et al. (1986) and found that replacing existing signs with signs that conform to MUTCD appear to reduce the number of injury and PDO accidents (p. 446) (*8*). The study found that improvements to make traffic signs on local streets conform to the MUTCD led to a 15% decrease in injury accidents, and a 7% decrease in PDO accidents. As a result of this one study being unique when reviewed as part of the meta-analysis process, Elvik and Vaa suggest using these values with caution. As shown in Exhibit 3-69, these percentages translate into AMF values of 0.85 (S=0.1) and 0.93 (S=0.06) for injury accidents and PDO accidents respectively. This study was considered to be of medium-high quality and the standard error values based on the confidence intervals reported by Elvik and Vaa have been multiplied with a method correction factor of 1.8 accordingly.

Exhibit 3-69: Safety effectiveness of installing signs to conform to MUTCD (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install signs to conform to MUTCD	Urban	Local streets, volume not reported	All types, Injury	0.85	0.1
Elvik and Vaa, 2004	Install signs to conform to MUTCD	Urban	Local streets, volume not reported	All types, PDO	0.93	0.06

Treatment: Install active close-following warning signs

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Elvik and Vaa conducted a meta-analysis of the safety impacts of a variety of signs and reported on a study by Helliar-Symon and Ray (1986) that investigated active close-following warning signs. These signs became illuminated and remained lit for 2 seconds when the gap between vehicles at an upstream detector was less than 1.6 seconds (p. 575) (*8*). The active message signs were rectangular in shape and were supplemented with four flashing amber beacons at each corner. Based on the findings from the meta-analysis by Elvik and Vaa, implementing active close-following warning signs on roadways has an AMF of 0.94 for total rear-end collisions (S = 0.72). This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 accordingly. The road type and traffic volumes for the study were not reported. The safety effects found are summarized in Exhibit 3-70.

Exhibit 3-70: Safety effectiveness of active close-following warning signs on road segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Active close-following warning signs	Not specified	Not specified	Rear-end crashes, severity not specified	0.94	0.72

Treatment: Install limited sight distance (LSD) warning signs

Rural two-lane roads

Forbes (2003) reports on a study by Kostyniuk and Cleveland (1986) of the effectiveness of "Limited Sight Distance" signs on paved two-lane roadways in Michigan (as cited in (*51*)). The traffic volumes were not reported in the study by Forbes. The signs comprised of a standard diamond-shaped, black on yellow warning sign with the legend "Limited Sight Distance". Using data available from the before-after study with a control group that was carried out by Kostyniuk and Cleveland, results show that installing limited sight distance signs on roadway segments has an AMF of 1.07 for total crashes (S = 0.67). The index of effectiveness and standard error values were estimated using the C-G method found in Hauer (*54*). The AMF value was increased by a factor of 0.05 to account for the effects of regression-to-mean (RTM) and a method correction factor of 1.5 was used to account for the study approach. The safety effects found are summarized in Exhibit 3-71.

Exhibit 3-71: Safety effectiveness of limited sight distance signs on road segments(as cited in (51))

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Kostyniuk and Cleveland, 1986	Limited Sight Distance signs	Rural	Paved 2-lane roadways, volumes not reported	All types, all severities	1.07	0.67

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Install changeable curve speed warning signs on horizontal curves

Rural two-lane roads

No studies found.

Rural multi-lane highways

Tribett et al. (2000) conducted a naïve before-after study that investigated the safety effects of using dynamic message signs (with varying messages depending on measured vehicle speeds upstream) to supplement existing static warning signs at horizontal curves in rural, mountainous areas (*52*). The message displayed was either the advisory speed for the curve or the operating speed of the approaching vehicle as measured using a radar speed-measuring device. The changeable message signs were 10 ft wide by 7 ft high with 18-inch lettering consisting of full matrix light-emitting diodes. At all five sites examined in the study, the speed limit was 65 mph (105 km/h) for passenger cars and 55 mph (89 km/h) for commercial trucks, while the advisory curve speed was 50 mph (80 km/h) at four of the five sites (the last site had a advisory curve speed of 60 mph or 97 km/h).

During the study, the speed limit for passenger cars was changed from 55 mph (89 km/h) to 65 mph (105 km/h) sometime during the before period at three of the five sites examined. Although the effect of this speed limit change on the results cannot be adequately quantified, it is likely that the non-truck-related crashes may have increased following the change.

Results from a naïve before-after comparison of the crash histories show that implementing changeable curve speed warning signs on rural highways with AADTs between 7,650 and 9,300 veh/day and a high percentage (35%) of truck volumes resulted in the AMFs summarized in Exhibit 3-72. This study was considered to be of low quality (5 years of data before, 6 months data after) and the standard error values have been multiplied with a method correction factor of 3 to account for this. In addition, the AMF values have been increased by a factor of 0.1 to account for RTM effects since the study sites were selected on the basis of high crash frequencies involving trucks. The use of this particular treatment appears to be effective in reducing truck-related crashes.

Exhibit 3-72: Safety effectiveness of changeable curve speed warning signs on horizontal curves

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Tribett et al., 2000	Changeable Curve Speed Warning signs	Rural, Mountainous	Multi-lane highways, 7650 to 9300 veh/day (with approx. 35% trucks)	All types, all severities	1.13	1.19
Tribett et al., 2000	Changeable Curve Speed Warning signs	Rural, Mountainous	Multi-lane highways, 7650 to 9300 veh/day (with approx. 35% trucks)	All types, injury	1.47	2.35
Tribett et al., 2000	Changeable Curve Speed Warning signs	Rural, Mountainous	Multi-lane highways, 7650 to 9300 veh/day (with approx. 35% trucks)	All types, PDO	0.98	1.38

Tribett et al., 2000	Changeable Curve Speed Warning signs	Rural, Mountainous	Multi-lane highways, 7650 to 9300 veh/day (with approx. 35% trucks)	Speed-related crashes, all severities	1.31	1.87
Tribett et al., 2000	Changeable Curve Speed Warning signs	Rural, Mountainous	Multi-lane highways, 7650 to 9300 veh/day (with approx. 35% trucks)	Truck-related crashes, all severities	0.29	0.96

Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Install horizontal alignment or combination horizontal alignment/ advisory speed signs (W1-1a, W1-2a)

Unspecified road type (Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials)

Elvik and Vaa (p. 361) (*8*) carried out a meta-analysis of a number of studies that examined the safety effects of static curve warning and recommended speed signs on horizontal curves. The road type, traffic volumes and other geometric features of the study sites were not reported by Elvik and Vaa. The results are summarized in Exhibit 3-73 and Exhibit 3-74. Based on the results from the meta-analysis conducted by Elvik and Vaa:

- Implementing static advance curve warning signs results in an AMF of 0.70 for injury accidents (S = 0.71).
- Implementing static advance curve warning signs results in an AMF of 0.92 for PDO accidents (S = 0.76).
- Implementing static recommended speed warning signs at horizontal curves results in an AMF of 0.87 for injury accidents (S = 0.09).
- Implementing static recommended speed warning signs results in an AMF of 0.71 for PDO accidents (S = 0.23).

Elvik and Vaa's meta-analysis was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-73: Safety effectiveness of horizontal alignment signs

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Advance curve warning signs	Not specified	Not specified	All types, Injury	0.70	0.71
Elvik and Vaa, 2004	Advance curve warning signs	Not specified	Not specified	All types, PDO	0.92	0.76

Exhibit 3-74: Safety effectiveness of combination horizontal alignment/ advisory speed signs (W1-1a, W1-2a)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Combination horizontal alignment/ advisory speed signs	Not specified	Not specified	All types, Injury	0.87	0.09
Elvik and Vaa, 2004	Combination horizontal alignment/ advisory speed signs	Not specified	Not specified	All types, PDO	0.71	0.23

Discussion: Qualitative evidence of safety improvements resulting from the implementation of signs at horizontal curves

All of the other research studies reviewed addressed the safety impacts of signs from the standpoint of reductions in vehicle speed rather than actual crashes. Although the link between surrogate measures such as speed and actual crashes has not been wholly established, it appears that the findings from these other studies that examine the effects of signing on speeds are counter-intuitive in light of the results established by Elvik and Vaa. However, this is not conclusive given the large standard errors associated with the results from the study by Elvik and Vaa.

Fitzpatrick et al. reviewed a previous study by Zwahlen (1987) that examined the effectiveness of advisory speed signs in conjunction with curve warning signs and found that advisory speed signs are not more effective in causing drivers to reduce their speeds through curves than curve and turn signs alone. Other studies by Lyles (1980a) and Agent (1975) that were reviewed and cited by Fitzpatrick et al. (*28*) appear to substantiate this finding. According to Fitzpatrick et al. (*28*), these studies found that various sign treatments for reducing traffic speeds in the vicinity of horizontal curves have generally been ineffective.

The Federal Highways Administration (FHWA) reviewed a study by Hanscom (1974) that examined the impacts of various types of skid warning signs at horizontal curves (*53*). Although Hanscom (1974) did not examine any crashes, the researcher reported that various configurations for "Slippery When Wet" signs resulted in reductions in the highest quartile mean speeds of vehicles in the vicinity of the curves. The researcher also found that these signs, with the addition of flashing lights and an advisory speed plate resulted in the largest decreases in vehicle speeds.

Treatment: Install changeable accident warning signs

Rural two-lane roads; Rural multi-lane highways; Expressways; Urban and suburban arterials

No studies found.

Freeways

Elvik and Vaa (p. 575) (*8*) examined one study that investigated the effect of dynamic accident warning signs on freeways and found that implementing dynamic/variable accident warning signs results in an AMF of 0.56 for injury accidents (S = 0.17). The traffic volumes were not reported. Elvik and Vaa's meta-analysis was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 to account for this. The safety effects are shown in Exhibit 3-75.

Exhibit 3-75: Safety effectiveness of dynamic/variable accident warning signs on roadway segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install changeable accident warning signs	Urban	Freeways, volume not reported	All types, Injury	0.56	0.17

Urban and suburban arterials

No studies found.

Treatment: Install changeable queue warning signs

Rural two-lane roads; Rural multi-lane highways; Expressways; Urban and suburban arterials

No studies found.

Freeways

Elvik and Vaa (p. 575) (*8*) carried out a meta-analysis of a number of studies that examined the safety effects of variable queue warning signs on freeways and reported that implementing these signs results in AMFs of 0.84 (S = 0.10) and 1.16 (S = 0.15) for rear-end injury and rear-end PDO accidents, respectively. The traffic volumes were not reported. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 to account for this. The safety effects are summarized in Exhibit 3-76.

Exhibit 3-76: Safety effectiveness of changeable queue warning signs on roadway segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Changeable queue warning signs	Not specified	Freeways, volume not reported	Rear-end, injury	0.84	0.10
Elvik and Vaa, 2004	Changeable queue warning signs	Not specified	Freeways, volume not reported	Rear-end, PDO	1.16	0.15

Urban and suburban arterials

No studies found.

Treatment: Install changeable speed warning signs

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Elvik and Vaa (p. 575) (*8*) conducted a meta-analysis of a number of studies that examined the safety effects of dynamic/variable speed warning signs on roadways segments and reported that:

- Implementing dynamic collective speed warning signs results in an AMF of 0.54 (S = 0.17) for total accidents.
- Implementing dynamic individual speed warning signs results in an AMF of 0.59 (S = 0.62) for injury accidents.

Elvik and Vaa defined individual feedback signs as those signs that provide information to the individual driver on his or her behavior (speed information, etc.) and collective signs as those that inform all drivers about the proportion of road users who have kept or broken a specific traffic rule such as the prevailing speed limit. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 to account for this. The road type, traffic volume and other geometric features of the study sites were not reported. The safety effects of this particular treatment are summarized in Exhibit 3-77. From the results reported by the authors, it appears that the use of collective and individual dynamic speed warning signs improve safety.

Exhibit 3-77: Safety effectiveness of changeable speed warning signs on road segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Collective [1] changeable speed warning signs	Not specified	Not specified	All types, all severities	0.54	0.17
Elvik and Vaa, 2004	Individual [1] changeable speed warning signs	Not specified	Not specified	All types, Injury	0.59	0.62

Note: 1 - Individual feedback signs give the individual information about his or her behavior while collective feedback signs give information showing the proportion of road users who have kept or broken a specific traffic rule (*8*).

3.2.2. Delineation

Delineation has long been considered an essential element for providing effective guidance to drivers on highways. Delineation typically refers to any method of defining the roadway operating area for drivers and may include delineation devices such as pavement markings made from a variety of marking materials, raised pavement markers (RPMs), pavement markers, and post-mounted delineators (PMDs) (*55*).

The MUTCD states that markings on highways have important functions in providing guidance and information for the road user. Major marking types include pavement and curb markings, object markers, delineators, colored pavements, barricades, channelizing devices and islands. In some cases, markings are used to supplement other traffic control devices such as signs, signals and other markings. In other instances, markings are used alone to effectively convey regulations, guidance, or warnings in ways not obtainable by the use of other devices (*50*).

The MUTCD adds that the visibility of pavement markings can be obscured by snow, debris, and water on or adjacent to the markings. Visibility can also be compromised since the durability of the pavement marking is affected by weather, its material properties, traffic volumes and location, and subsequently degrades (*50*).

In the case of delineation devices such as post-mounted delineators, the MUTCD states that they can be particularly beneficial at locations where the alignment might be confusing or unexpected, such as at lane reduction transitions and curves. Delineators are effective guidance devices at night and during adverse weather. An important advantage of some delineators in certain locations is that they remain visible when the roadway is wet or snow covered since they are required to be retroreflective and mounted above the roadway surface and along the side of the roadway in a series to indicate the alignment.

The MUTCD presents standard ways of conveying information to the driver through the design, color, pattern and width of the pavement marking. For example, yellow lines separate traffic flowing in opposing directions, whereas white lines denote traffic flowing in the same direction (*55*). A double line indicates maximum or special restrictions; a solid line discourages or prohibits crossing (depending on the specific application); a broken line indicates a permissive condition; and a dotted line provides guidance (*50*). The MUTCD contains detailed standards related to color, pattern, and width of pavement markings, which are not repeated here.

In terms of retroreflectivity requirements, the MUTCD stipulates that delineators are required to have retroreflective elements with a minimum dimension of 3 in (75 mm) and be capable of retroreflecting light under normal atmospheric conditions from a distance of 1,000 ft (300 m) when illuminated by the high beams of standard automobile lights.

This section investigates the safety effects of the different delineation practices typically used to regulate, warn or provide guidance to drivers when traversing any particular road segment, and excludes any examination of intersections. The treatments examined here include post-mounted delineators, chevron signs, raised buttons, high-visibility stripes, pavement markers (including snowplowable, recessed, raised, and illuminated/solar markers), various types of longitudinal and transverse pavement markings and combinations of these treatments. In addition, this section also attempts to address the safety impacts of maintenance practices associated with these types of delineation treatments.

The safety effectiveness of delineation treatments at intersections is discussed in Chapter 4.

Exhibit 3-78: Resources examined to investigate the safety effect of delineation on road segments

DOCUMENT	DESCRIPTION	COMMENT
(Lord, D., J.A. Bonneson, "Development of Accident Modification Factors for Rural Frontage Road Segments in Texas", Transportation Research Board 86th Annual Meeting, Washington D.C., (2007))	Developed AMF values for the presence of edge line delineation along rural frontage roads in Texas.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-28 "Pavement Marking Materials and Markers: Safety Impact and Cost-Effectiveness" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-28	On-going project.	Results not available.
Transportation Association of Canada "Best Practice Guidelines for the Design and Application of Transverse Rumble Strips" (2005)	Synthesis of other research.	No new results. Not added to synthesis.
(Smiley, A., "Speed-Reducing Countermeasures." (2004))	The paper reviews various studies of countermeasures designed to reduce speed and crashes.	Not added to synthesis. No AMFs found.
(*57*) (Bahar, G., Mollett, C., Persaud, B., Lyon, C., Smiley, A., Smahel, T., and McGee, H., "NCHRP Report 518: Safety Evaluation of Permanent Raised Pavement Markers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Study involved an empirical Bayesian before-after safety analysis to quantify safety effectiveness of snowplowable PRPMs.	Added to synthesis; t values taken directly from report, s values calculated using procedure.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report focuses on strategies to prevent the crash types prevalent on horizontal curves.	Not added to synthesis. Improvements in surrogate measures (such as vehicle speeds entering the curves and the lateral placements of vehicles along the horizontal curve) resulting from treatments such as post-mounted delineators and chevrons were discussed in review of study by Neuman et al. (2003)
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis.
(*16*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Review of past studies researching the effectiveness of various treatments to address run-off-road crashes.	Added to synthesis. Quantitative evidence of crash reduction found although there is insufficient data to calculate t and s values. Surrogate measures (i.e., speed and lateral position of vehicles) is presented.
(*51*) (Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Study reviews and brings together the best available evidence on the safety impact of traffic operations. All the studies reviewed report on crash occurrence, severity or proven crash surrogates.	Added to synthesis. Only qualitative information used. Several studies reviewed offer quantitative data but went back to original studies for data to calculate t and s.

DOCUMENT	DESCRIPTION	COMMENT
(Storm, R., "Pavement Markings and Incident Reduction." Ames, Iowa, 2000 MTC Transportation Scholars Conference, (2000) pp. 152-162.)	Reference identifies the areas where pavement markings are most likely to reduce crashes and focuses on the application of pavement markings in three areas: horizontal curvature, turning movements, and pedestrian crosswalks.	Suggested by NCHRP 17-18(4). Not added to synthesis. Limited quantitative information found.
(*28*) (Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways through a review of previous studies.	Added to synthesis. No AMFs related to delineation were found although there is anecdotal evidence of crash reductions due to PMDs.
(*58*) (Reinfurt, D., Zegeer, C., Shelton, B., Neuman, T.R., "Analysis of Vehicle Operations on Horizontal Curves" Transportation Research Record 1318 (1998))	The study investigated vehicle operations such as encroachment on left and right curves.	Limited qualitative information added to synthesis.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Reviews existing research and attempts to provide guidelines on highway engineering improvements that would help older drivers and pedestrians.	Not added to synthesis.
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	Study reviewed the relationships between safety, speed limits and speed zoning practices through a review of previous research efforts.	Not added to synthesis. Used data from original study by Griffin and Reinhardt to calculate t and s values.
(*60*) (Griffin, L. I. and Reinhardt, R. N., "A Review of Two Innovative Pavement Patterns that Have Been Developed to Reduce Traffic Speeds and Crashes." Washington, D.C., AAA Foundation for Traffic Safety, (1996))	Study reviews the effectiveness of converging chevron pattern road markings and transverse bar pattern markings.	Added to synthesis. t and s values calculated using reduction in crashes and 95% confidence interval range provided by researchers
(*55*) (Migletz, J., Fish, J. K, and Graham, J. L., "Roadway Delineation Practices Handbook." FHWA-SA-93-001, Washington, D.C., Federal Highway Administration, (1994))	Supplemental reference document to the policies and standards pertaining to delineation treatments provided in the MUTCD.	Added to synthesis. No AMFs found although according to the researchers, the implementation of PMDs has resulted in a reduction in accident rates.
(*61*) (Al-Masaeid, H. R. and Sinha, H., "An Analysis of Accident Reduction Potentials of Pavement Marking." (1993))	Evaluated the effect of safety of pavement markings used on undivided rural roads; 100 roads in Indiana	Suggested by NCHRP 17-18(4). Added to synthesis; t and s values relevant to Pavement Markings and Markers calculated using procedure.

DOCUMENT	DESCRIPTION	COMMENT
(Miller, T. R., "Benefit-Cost Analysis of Lane Marking." Transportation Research Record 1334, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 38-45.)	Evaluated the safety benefits of longitudinal pavement markings, in particular for high solvent paint and thermoplastic markings	Suggested by NCHRP 17-18(4). Not added to synthesis. Quantitative evidence of crash reduction found although there is insufficient data to calculate t and s values using our procedures.
(*62*) (Lalani, N, "Comprehensive Safety Program Produces Dramatic Results." ITE Journal, Vol. 61, No. 10, Washington, D.C., Institute of Transportation Engineers, (1991) pp. 31-34.)	Study included a naïve before-after study of a variety of treatments including installation of traffic signals, signal coordination, and installation of chevron signs among others.	Added to synthesis; t and s values calculated using available before and after accident data.
(*63*) (Kallberg, V., "Reflector Posts - Signs of Danger?" Transportation Research Record 1403, Washington, D.C., Transportation Research Board, National Research Council, (1990) pp. 57-66.)	Study investigated the impacts of reflector posts (post-mounted delineators) on speeds and nighttime accidents	Added to synthesis for additional information. Quantitative evidence of safety impacts from this research work already summarized as part of meta-analysis by Elvik and Vaa in their Handbook.
(*64*) (Agent, K. R. and Creasey, F. T., "Delineation of Horizontal Curves." UKTRP-86-4, Frankfort, Ky., Kentucky Transportation Cabinet, (1986))	Investigates the effect of traffic control devices such as raised pavement markings and signs on driver behavior at horizontal curves	Suggested by NCHRP 17-18(4). Added to synthesis.
(Glennon, J. C., "Accident Effects of Centerline Markings on Low-Volume Rural Roads." Transportation Research Record 1027, Washington, D.C., Transportation Research Board, National Research Council, (1985) pp. 7-13.)	Compared the crash experience of various centerline treatments used on low-volume rural roads; used Pavement Marking Demonstration Program data	Suggested by NCHRP 17-18(4). Not added to synthesis. Insufficient data needed for calculation of t and s values.
(*53*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis study reviewing 17 safety research areas.	Added to synthesis. Quantitative evidence of crash reduction found although there is insufficient data to calculate t and s values.
(Dawson, R. F. and Oppenlander, J. C., "General Design." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 11, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Reference discusses the relationship between safety and general design features of highways mainly in terms of accident rates and costs.	Not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reference discusses the relationship between accidents and cross sectional elements.	Not added to synthesis.

Based on the critical review, few studies have investigated the safety impacts of delineation treatments other than post-mounted delineators and chevron signs for road segments. The large majority of safety studies related to delineation treatments on road segments typically deal with pavement markings or markers. The majority of safety studies are limited to anecdotal information.

Very few of the references identified provide sufficient information to quantify the safety impacts of pavement marking and markers on roadway segments. The quantitative information contained for pavement markings within this section is largely derived from the meta-analysis research conducted by Elvik and Vaa (*8*) while the quantified safety impacts of snowplowable PRPMs is taken from a recent NCHRP study (*57*). Where available, the effectiveness of a variety of pavement markings and markers has been distinguished by setting, roadway type, and in the case of horizontal curves, the degree of curvature. Given the heavy reliance on meta-analysis studies that essentially combined studies with varying traffic volumes, road types and setting, it was not always possible to discern the specific ranges of applicability such as the road class, environment type, and traffic volume ranges.

Treatment: Install post-mounted delineators (PMDs)

Rural two-lane roads

From the review of studies, it appears that few researchers have investigated the safety impacts of post-mounted delineators in isolation from other treatments. The majority of studies have typically examined sites where PMDs were used in conjunction with other delineation treatments such as chevrons, raised pavement markers (RPMs) and pavement markings. Only the study by Elvik and Vaa (p. 541) (*8*) provided sufficient quantitative data to calculate indices of effectiveness and standard error values to quantify the safety effectiveness of post-mounted delineators.

Elvik and Vaa (*8*) estimated the safety effect of installing post-mounted delineators on two-lane, undivided rural roads. Based on the meta-analysis that was conducted, the implementation of this particular treatment results in AMF values of 1.04 (S = 0.10) and 1.05 (S = 0.07) for injury accidents and PDO accidents, respectively. Note that Elvik and Vaa combined studies that investigated the safety effect of post-mounted delineators installed along tangents as well as curves.

This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this. The safety effects for this particular treatment are summarized in Exhibit 3-79.

Exhibit 3-79: Safety effectiveness of post-mounted delineators on roadway segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install post-mounted delineators	Rural	Two-lane undivided, volumes not reported	All types, Injury	1.04	0.10
Elvik and Vaa, 2004	Install post-mounted delineators	Rural	Two-lane undivided, volumes not reported	All types, PDO	1.05	0.07

Although Elvik and Vaa did not provide any additional information on the road class, traffic volume ranges and environment type for the sites examined, further review of one of the original studies that formed part of the meta-analysis by Elvik and Vaa suggests that the negative impacts of post-mounted delineators occur on roads with lower geometric standards. The original study by Kallberg (*63*) concluded that on roads with comparatively low geometric standards, “reflector posts have a negative effect on driving behavior that significantly increases accident risk” while on wider roads with higher geometric standards, “such negative effects are rare and reflector posts do not necessarily reduce safety”. It should be noted that the study was conducted in Finland and there are potential differences in driver behavior and attitude. As Kallberg explains, drivers in Finland generally consider 62 mph (100 km/h) as an ideal or target speed, irrespective of the geometric design of the roadway (*63*), suggesting that Finnish drivers may be more inclined to drive at higher speeds. In some cases, the improved visual guidance provided by reflector posts/post-mounted delineators actually encourages drivers to drive faster as they are naturally inclined to do, regardless of the prevailing geometric design standards of the roadway (*63*).

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Discussion: Implementation of post-mounted delineators at horizontal curves and crashes

Other studies reviewed do not provide sufficient information to calculate indices of effectiveness and standard error values but they did provide some additional quantitative information on the safety effectiveness of post-mounted delineators. Neuman et al. (2003) reviewed a previous research study conducted by Foody and Taylor (1966) and found that implementing post-mounted delineators on sharp curves reduced run-off-road (ROR) crashes by 15% (*16*). Another recently-published reference by Fitzpatrick et al. (2000) presented the findings from a literature review of previous research efforts by Hall (1987), Longenecker (1980), Tamburri et al. (1967), Taylor et al. (1972), and reported that “post-mounted roadside delineation reduced the accident rate only on relatively sharp curves during periods of darkness” (*28*). On the basis of findings from a study by the Arizona Highway Department (1963), Fitzpatrick et al. further added that PMDs did not have “any significant effect” on the accident rates of open tangent sections.

These conclusions appear to be in conflict with another study that was conducted by Capelle (1978) and reviewed by Fitzpatrick et al. (*28*). Findings from that particular study appear to indicate that PMDs do have an effect on safety and that “the highways with PMDs (in the absence or presence of edgelines) have lower accident rates than those without PMDs” (*28*).

Migletz et al. (1994) appeared to concur stating that accident rates are significantly lower where PMDs are used and that “a reduction of approximately 1 accident per million vehicle-miles (0.6 accidents per million vehicle-kilometers) has been demonstrated” (*55*). Migletz et al. also stated that accident analyses have shown a lower accident rate at isolated horizontal curves where PMDs supplemented standard painted markings but did not provide any quantifiable measures since the sample size used was “too small to make a definitive conclusion” (*55*).

A synthesis study by the FHWA (1982) reviewed the work of Niessner (1982) who evaluated the impacts of using PMDs and found that the accident data collected "indicates a trend toward reducing ROR accidents where PMDs are installed" (*53*). It is unclear how conclusive these particular findings are, given the lack of information about the local policies related to the implementation of such delineation treatments, the road types in question, the geometric elements of the roadway, and the traffic volumes among other issues.

Discussion: Implementation of post-mounted delineators at horizontal curves and other measures (speed, lateral placement of vehicle, etc.)

From the review of references, it appears that many researchers have investigated the impacts of PMDs using surrogate measures such as the speeds of vehicles approaching and traversing horizontal curves, and/or the lateral placement of these vehicles. The study by Neuman et al. (2003) reviewed a number of studies [Zador et al. (1987); Kallberg (1993); Retting and Farmer (1998); Retting (1999); Meyer (2001); Agent (1980); Retting et al. (2000); Steyvers and Ward (1997)] and concluded that even though the "specific effects of reflector posts on the lateral position remain unclear, it is clear that the shift in lateral position (if there is a significant shift) is toward the edge of the road" (*16*).

This finding should be viewed in light of the results from a number of previous research studies that have established that in general, there are few edgeline encroachments regardless of whether the horizontal curve is to the left or right, except at locations where there are sharp, right curves. These studies have shown that the greater the deflection angle, the more edgeline encroachments for right curves and centerline encroachments for left curves. This phenomenon can be attributed to the tendency of drivers to undercut the curve and potentially increase the risk of run-off-road crashes on right curves and head-on crashes on left curves (*58*).

A more recent review by Forbes of a study conducted by Zador et al. (1987) shows the authors concluding that the implementation of PMDs, chevrons and raised pavement markers (RPMs) on horizontal curves all resulted in increased night-time driving speeds (*51*). These results appear to be similar to the findings from another recent study by Bahar et al. that examined the safety effects of PRPMs at horizontal curves and concluded that drivers tend to under compensate (i.e., not reduce speeds enough) in poor visibility conditions and for roadway segments with lower geometric standards (*57*). Bahar et al. state that the implementation of treatments such as PRPMs caused drivers to move away from the delineation measures when driving at night or under poor visibility conditions. For example, in the case of centerline PRPMs, drivers will move away from the centerline toward the shoulder. While this behavior may reduce the incidence of opposing direction (e.g., head-on) crashes, it may increase run-off-road crashes, especially on roads with lower design standards (i.e., with narrow and/or gravel shoulders). A human factors review by Bahar et al. also found some evidence that PRPMs may actually cause drivers to increase their speeds (*57*). Speed increases at locations where drivers already operate close to the margin of safety (e.g., sharp curves) may result in an increased number of crashes.

Treatment: Install chevron signs on horizontal curves

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Lalani investigated the safety impacts of a variety of treatments in the City of San Buenaventura (California), including the installation of chevron signs on horizontal curves using a naïve before-after study approach (*62*). As shown in Exhibit 3-80, adding chevron signs to horizontal curves in an urban setting has an AMF of 0.36 (S=0.49) for total crashes. This study was considered to be of low quality (naïve before-after study with 1 year of data before, 1 year of data after) and the standard error values have been multiplied with a method correction factor of 3.0 to account for this. In addition, the AMF values have been increased by a factor of 0.25 to account for RTM effects resulting from the short before and after study periods, and the fact that the study sites were selected on the basis of high crash frequencies.

Exhibit 3-80: Safety effectiveness of chevron signs on horizontal curves (62)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lalani (1991)	Chevron signs on curves	Urban	Urban/suburban arterials, volume not reported	All accidents, all severities	0.36	0.48

Discussion: Chevrons at horizontal curves on other measures (speed, lateral placement of vehicle, etc.)

Bahar et al. reviewed a human factors study by Zwahlen and Park (1995) that investigated the impact of chevrons and reported that chevrons can be seen considerably further than PRPMs because of their orientation, and there is no reduction in visibility with rain (*57*). On the basis of the findings from Zwahlen and Park, Bahar et al. concluded that chevrons seem to be preferable to PRPMs on sharp curves (*57*). Studies of the relationship between speed in curves and curve geometry show that curve radius and curve angle are important predictors of speed. Studies of driver response show that drivers viewing images of curves (i.e. equivalent to unfamiliar drivers with no experience of the curve) indicate that the deflection angle curve is more important than the radius in determining approach speed.

For these reasons, chevron markers which delineate the entire curve angle are generally recommended on sharp curves. Studies of the effect of chevron signs on lateral placement, speed and speed variance indicate that their effects are modest. A before-after study of chevrons, post mounted delineators and other road edge delineators showed chevrons to be best on curves with deflection angles greater than seven degrees (Jenning & Demetsky, 1985 as cited in (*57*)). On these curves, after installation, lane encroachment was reduced. Speeds, although slightly higher than for the other markings (by a maximum of two percent), were less variable.

Treatment: Place standard edgeline markings (100 to 150 mm or 4 to 6 in)

Rural two-lane roads

Elvik and Vaa conducted a meta-analysis of studies related to the installation of normal edgelines with widths ranging between 100 to 150 mm (4 to 6 in.) and found that implementing this treatment on two-lane, undivided rural roads reduces the number of injury and PDO accidents (p. 541) (*8*). As shown in Exhibit 3-81, Elvik and Vaa found that the installation of normal edgelines on roadway segments has AMF values of 0.97 (S=0.04) and 0.97 (S=0.11) for injury accidents and PDO accidents respectively. The traffic volumes at the sites examined were not reported. Elvik and Vaa's meta-analysis was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 accordingly.

Exhibit 3-81: Safety effectiveness of placing standard edgeline markings (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, tadjusted	Estimate of Std. Error, s
Elvik and Vaa, 2004	Placing standard edgeline markings	Rural	Mostly two-lane undivided, volume not specified	All types, Injury	0.97	0.04
Elvik and Vaa, 2004	Placing standard edgeline markings	Rural	Mostly two-lane undivided, volume not specified	All types, PDO	0.97	0.11

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Place wide edgeline markings (200 mm or 8 in)

Rural two-lane roads

Elvik and Vaa conducted a meta-analysis of studies related to the installation of wide edgelines (200 mm or 8 in.) and based on the best estimates for percentage change in accidents, found that implementing this particular treatment results in modest changes to both injury and PDO accidents (p. 541) (*8*). The results are inconclusive with respect to whether the treatments actually reduce or increase accidents, given the values of the AMFs developed and corresponding standard error values. As shown in Exhibit 3-82, Elvik and Vaa found that the installation of wide edgelines on roadway segments has AMF values of 1.05 (S=0.08) and 0.99 (S=0.15) for injury accidents and PDO accidents respectively. The traffic volumes at the sites examined were not reported. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 accordingly.

Exhibit 3-82: Safety effectiveness of placing wide edgeline markings (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Placing wide edgeline markings	Rural	Mostly two-lane undivided, volume not specified	All types, Injury	1.05	0.08
Elvik and Vaa, 2004	Placing wide edgeline markings	Rural	Mostly two-lane undivided, volume not specified	All types, PDO	0.99	0.15

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Place centerline markings on roadway segments

Rural two-lane roads

Elvik and Vaa conducted a meta-analysis of studies related to the installation of centerlines on undivided highways and based on the best estimates for percentage change in accidents, found that implementing this treatment results in modest changes to injury and PDO accidents (p. 541) (*8*). Given the AMF and standard error values developed using the results from the study, it is inconclusive as to whether the treatments increase or decrease the number of accidents. As shown in Exhibit 3-83, Elvik and Vaa found that the installation of centerlines on undivided roadway segments has AMF values of 0.99 (S=0.06) and 1.01 (S=0.05) for injury accidents and PDO accidents respectively. The traffic volumes were not reported. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 accordingly.

Exhibit 3-83: Safety effectiveness of placing centerline markings (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Placing centerline markings	Mixed urban and rural	Mostly two-lane undivided, volume not specified	All types, Injury	0.99	0.06
Elvik and Vaa, 2004	Placing centerline markings	Mixed urban and rural	Mostly two-lane undivided, volume not specified	All types, PDO	1.01	0.05

Rural multi-lane highways; Urban and suburban arterials

No studies found.

Treatment: Add lane line markings on multi-lane roadway segments

Rural two-lane roads

Not applicable.

Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Elvik and Vaa conducted a meta-analysis of studies related to the addition of lane lines on multilane urban roadways and based on the best estimates for percentage change in accidents, found that implementing this treatment reduces the total accidents (p. 541) (*8*). As shown in

Exhibit 3-84, Elvik and Vaa found that the installation of lane lines on multilane roadway segments in an urban environment has an AMF value of 0.82 (S=0.39) for total accidents. The traffic volumes were not reported. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 accordingly. In the United States, most multi-lane facitilities have lane line markings according the MUTCD; thus the treatment may not be applicable.

Exhibit 3-84: Safety effectiveness of installing lane lines on multilane roadway segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing lane lines	Urban	Multilane, volume not specified	All types, all severities	0.82	0.39

Treatment: Provide distance markers

Rural two-lane roads; Rural multi-lane highways; Expressways; Urban and suburban arterials

No studies found.

Freeways

Elvik and Vaa reviewed one British study by Helliar-Symons et al. (1995) that investigated the installation of distance markers on motorways (the British equivalent to freeways) and based on the best estimates for percentage change in accidents, found that implementing this treatment significantly reduces the injury accidents. Distance markers are angle or chevron symbols marked on the carriageway to help drivers maintain an adequate distance from the vehicles in front (p. 541) (*8*). As shown in Exhibit 3-85, Elvik and Vaa found that the installation of distance markers (angle symbols) on motorways/expressways has an AMF value of 0.44 (S=0.26) for injury accidents. The traffic volumes were not reported. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 to accordingly.

Exhibit 3-85: Safety effectiveness of installing distance markers (angle symbols) on roadway segments (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing distance markers	Not specified	Freeways, volume not specified	All types, Injury	0.44	0.26

Urban and suburban arterials

No studies found.

Treatment: Place combination of edgelines and background/ directional markings on horizontal curves

Rural two-lane roads

Elvik and Vaa conducted a meta-analysis of studies related to the installation of edgelines and background/directional markings on horizontal curves. Based on the best estimates for percentage change in accidents, the researchers found that implementing this combined treatment is expected to reduce the number of single-vehicle run-off-road (SV ROR) injury accidents (p. 541) (*8*). As shown in Exhibit 3-86, Elvik and Vaa found that the installation of edgelines and background/directional markings on horizontal curves for two-lane, undivided rural roads has an AMF value of 0.81 (S=0.31) for injury accidents. Although the traffic volumes were not reported, it is expected that they were likely to be in the lower range (AADT < 5,000 veh/day). This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 accordingly.

Exhibit 3-86: Safety effectiveness of edgelines and background/directional markings on horizontal curves (8)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Placing edgelines and background/ directional markings on horizontal curves	Rural	Two-lane undivided, not specified	Single-vehicle run-off-road (SV ROR), Injury	0.81	0.31

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Install raised pavement markers and transverse rumble strips on approach to horizontal curves

Rural two-lane roads

Elvik and Vaa conducted a meta-analysis of studies related to the installation of raised pavement markers (RPMs) and transverse rumble strips on the approach to horizontal curves. Based on the best estimates for change in accidents, the researchers found that implementing this combined treatment reduces SV ROR injury accidents (p. 541) (*8*). As shown in Exhibit 3-87, Elvik and Vaa found that the installation of RPMs and background/directional markings on horizontal curves has an AMF value of 0.94 (S=0.49) for SV ROR injury accidents. The traffic volumes were not reported. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 accordingly.

Agent and Creasey (*64*) investigated the use of transverse markings, rumble strips and raised pavement markers to delineate horizontal curves on two-lane, undivided rural roads. The type and design of the rumble strips and raised pavement markers, and the volumes and posted speeds at the study sites were not specified in the paper. Although the traffic volumes were not reported, it is expected that they were likely to be in the lower range (AADT < 5,000 veh/day). Regression to the mean is likely due to site selection bias; therefore the AMFs were corrected by a multiplicative factor of 0.1. This study was considered to be of low quality and the standard error values have been multiplied with a method correction factor of 3.0 accordingly, and then corrected for the RTM bias. The resulting standard errors are quite large, primarily due to the small number of crashes in the study.

Exhibit 3-87: Safety effectiveness of combination of raised pavement markers and transverse rumble strips on approach to horizontal curves

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing RPMs and background/ directional markings on horizontal curves	Rural	Two-lane undivided, volume not reported	Single-vehicle run-off-road (SV ROR), Injury Accidents	0.94	0.49
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	All types, all severities	1.10	1.26
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	Wet accidents, all severities	0.91	1.16
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	Nighttime accidents, all severities	0.83	1.88
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	All types, all severities	0.47	0.50
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	Wet accidents, all severities	0.51	0.55
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	Nighttime accidents, all severities	0.36	1.37

NOTE: *For this site, the westbound direction had transverse rumble strips and RPMs while the eastbound direction had transverse pavement markings and RPMs

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Place edgelines and centerlines on roadway segments

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Elvik and Vaa conducted a meta-analysis of studies related to the addition of both edgelines and centerlines on previously unmarked roadway segments and based on the best estimates for change in accidents, the researchers found that implementing this combined treatment significantly reduces the injury accidents (p. 541) (*8*). The sites used in the studies that were meta-analyzed represented a mixture of urban and rural, two-lane and multi-lane roadways. The traffic volumes were not reported. Elvik and Vaa found that the installation of edgelines and centerlines has an AMF value of 0.76 (S=0.11) for injury accidents. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 accordingly (Exhibit 3-88).

Al-Masaeid and Sinha (p. 9) (*61*) investigated the safety effectiveness of edgelines and centerlines on undivided rural roads and concluded that overall, the use of such treatments were not effective in reducing accident rates and may in fact result in a slight increase in total crashes but for "hazardous sites"[2], they appeared to reduce the total number of crashes. The researchers found that the installation of edgelines and centerlines resulted in an AMF value of 1.034 (S=0.25) for total accidents when all sites were considered and an AMF value of 0.865 (S=0.25) for total accidents for hazardous sites only. This study was considered to be of low quality (markings in before period not reported) and the standard error values have been multiplied with a method correction factor of 3 accordingly.

The study results were not combined due to the differences in crash severity, and are provided in Exhibit 3-88.

[2] Al-Masaeid and Sinha defined hazardous sites as sites which had accident rates exceeding the overall mean in the before period (*61*).

Exhibit 3-88: Safety effectiveness of edgelines and centerlines on roadway segments

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing edgelines and centerlines	Mixed urban and rural	Mixed two-lane and multilane, volume not specified	All types, Injury	0.76	0.11
Al-Masaeid and Sinha, 1993	Installing edgelines and centerlines	Rural	Undivided, 1,000 to 4,000 veh/day	All types, all severities	1.03	0.25
Al-Masaeid and Sinha, 1993	Installing edgelines and centerlines at sites with higher incidences of crashes	Rural	Undivided, 1,000 to 4,000 veh/day	All types, all severities	0.87	0.14

Freeways; Expressways

No studies found.

Treatment: Install edgelines, centerlines and post-mounted delineators on roadway segments

Rural two-lane roads; Rural multi-lane highways

Elvik and Vaa conducted a meta-analysis of studies related to the installation of edgelines, centerlines and delineators on roadway segments and based on the best estimates for change in accidents, the researchers concluded that implementing this combined treatment significantly reduces the injury accidents (p. 541) (*8*). The sites used in the studies that were meta-analyzed were comprised of a mixture of urban and rural, two-lane and multi-lane roadways. The traffic volumes were not reported. As shown in Exhibit 3-89, Elvik and Vaa found that the installation of edgelines, centerlines and delineators has an AMF value of 0.55 (S=0.11) for injury accidents. This study was considered to be of medium-high quality and the standard error value has been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-89: Safety effectiveness of edgelines, centerlines and post-mounted delineators

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install edgelines, centerlines and delineators	Mixed urban and rural	Mixed two-lane and multilane, volume not specified	All types, Injury	0.55	0.11

Freeways; Expressways; Urban and suburban arterials

No studies found.

Treatment: Install snowplowable permanent RPMs on roadway segments

Rural two-lane roads; Freeways

Bahar et al. conducted a study investigating the safety impacts of snowplowable RPMs on two-lane roadways, four-lane freeways and four-lane divided expressways using an empirical Bayesian before-after study approach (*57*). Using regression techniques, safety performance functions (SPFs) and accident modification functions (AMFs) were developed for two-lane roadways and four-lane freeways. Although the study by Bahar et al. (*57*) also attempted to quantify the safety effects of snowplowable RPMs for four-lane divided expressways, the effort was unsuccessful due to data constraints.

Bahar et al. reported that the selective implementation of RPMs requires careful consideration of traffic volumes and roadway geometry seeing that the results from the study show that RPMs can in fact be associated with a negative safety effect, particularly in the presence of sharp curves (*57*). The indices of effectiveness of snowplowable RPMs on nighttime crashes and the corresponding values of standard error for two-lane roadways and four-lane freeways are summarized in Exhibit 3-90 and Exhibit 3-91, respectively. Due to the rigorous methodology applied, this study was considered to be of high quality and the standard error value has been multiplied with a method correction factor of 1.2 accordingly.

Exhibit 3-90: Safety effectiveness of snowplowable permanent RPMs on two-lane roadway segments (57)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC ≤ 3.5, AADT = 0 to 5000	Nighttime, all severities	1.16	0.03
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC > 3.5, AADT = 0 to 5000	Nighttime, all severities	1.43	0.10
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC ≤ 3.5, AADT = 5001 to 15000	Nighttime, all severities	0.99	0.06
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC > 3.5, AADT = 5001 to 15000	Nighttime, all severities	1.26	0.11
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC ≤ 3.5, AADT = 15001 to 20000	Nighttime, all severities	0.76	0.08
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	2-lane roadways with DOC > 3.5, AADT = 15001 to 20000	Nighttime, all severities	1.03	0.13

DOC = Degree of Curvature

Exhibit 3-91: Safety Effectiveness of Snowplowable PRPMs on Four-Lane Freeways

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	4-lane freeways with controlled access, AADT < 20000	Nighttime, all severities	1.13	0.16
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	4-lane freeways with controlled access, AADT = 20001 to 60000	Nighttime, all severities	0.94	0.25
Bahar et al., 2004	Implementation of snowplowable PRPMs	Primarily rural	4-lane freeways with controlled access, AADT < 60000	Nighttime, all severities	0.67	0.25

Urban and suburban arterials; Rural multi-lane highways; Expressways

No studies found.

Discussion: Differences in the impact of PRPMs on roads with high and low design standards

As part of the study conducted by Bahar et al. (*57*), the researchers provided a detailed discussion on the effects of implementing PRPMs on the number of crashes as well as other surrogate measures such as vehicle speeds and lane positioning as reported by other publications. Through a review of previous research studies and on the basis of their own study results, Bahar et al. proposed that vehicle speeds generally increased at night following improved delineation, resulting in increased crash frequency, particularly for roads with low design standards. The researchers further noted that there are indications through other studies that drivers are reluctant to decrease their speeds by too much and are often willing to trade off comfort for time savings. Subsequently, on sharper horizontal curves (i.e. with a higher degree of curvature), it seems that the negative safety impact of speed increases is not offset by the positive safety impact of improved visibility (*57*).

Treatment: Apply converging chevron pattern markings on roadway segments

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Griffin and Reinhardt carried out a study that investigated the impacts of implementing converging chevron pavement marking patterns on urban roadways and found a 38.4 percent reduction in total crashes (*60*). The chevrons used in the study were comprised of both standard and anti-skid materials. The standard chevron is a white, painted or thermoplastic “V” that points in the direction of travel. The researchers reported an overall reduction of 38.4 percent in total crashes with 95 percent confidence that the true reduction factor is between 25.3 percent and 49.2

percent. The study approach comprised of a simple before-after study and the reviewers provided a warning about the possibility of the presence of a regression-to-the-mean bias in the findings. Subsequently, the index of effectiveness from this particular reference was increased by a multiplicative factor of 0.1 to account for the regression-to-the-mean phenomenon. This study was considered to be of low quality and the standard error value has been multiplied with a method correction factor of 3 to account for the study approach. As shown in Exhibit 3-92, the reported percentage reduction translates into an AMF values of 0.68 (S=0.19) for total accidents. The traffic volumes were not reported.

Exhibit 3-92: Safety effectiveness of converging chevron pattern markings on roadway segments

Study, date	Treatment/ element	Setting	Road type, volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Griffin and Reinhardt (1996)	Implementation of converging chevron pattern on road surface.	Urban	Unspecified	All types, all severities	0.68	0.19

3.2.3. Rumble Strips

Rumble strips are used to provide a vibrotactile or audible warning to motorists. They are intended to reduce crashes caused by drowsy or inattentive motorists. In this edition of the HSM, this section will provide information on the safety effects of using shoulder, centerline or transverse rumble strips on roadway segments. Future editions of the HSM may address other types of rumble strip applications on sections, such as edgeline or mid-lane rumble strips.

Several concerns have been identified regarding the use of rumble strips, which apply to all types of rumble strips:

- Noise
- Maintenance
- Bicyclists
- Motorcyclists
- Improper driver reaction
- Crash migration

Noise is a valid concern, as rumble strips cause noise external to the vehicle, and may affect surrounding residents. It is generally accepted that rumble strips should not be used near residences or in other locations where the noise they generate is likely to disturb people. Agencies including Alaska, Colorado, Delaware, and Pennsylvania consider noise impacts before implementing in residential or urban areas (based on a survey conducted for NCHRP 34-01 by Russell, E. R. and Rys, M. J., "Centerline Rumble Strips." (draft unpublished 2004)). Studies show that rumble strips that are terminated 200 m prior to residential or urban areas produce tolerable noise impacts on residences. At an offset of 500 m, the noise from rumble strips is negligible (*66*).

The remaining concerns have not been substantiated with empirical evidence. In many cases, these concerns have proven to be unfounded by researchers and practitioners. In summary:

- Maintenance: “States that use rumble strips (on the roadway shoulder or otherwise) have not reported any additional maintenance requirements as long as the rumble strips are placed on pavement that is in good condition.” (*67*).
- Bicyclists: Rumble strips can be designed to minimize the discomfort to bicyclists, as determined by Torbic et al. (*68*). The decision to implement rumble strips may depend on the presence of bicyclists on the route.
- Motorcyclists: “Pennsylvania has worked with motorcycle groups, and no major concerns were raised by these groups.” (*67*).
- Improper driver reaction: Several studies have found that although some driver’s initially react incorrectly to rumble strips, the majority of drivers react in the desired way. It is anticipated that as the driving public become more familiar with rumble strips, the percentage of driver’s with an initial incorrect reaction will decline (*69*).
- Crash migration: Analysis of downstream collision data by Griffith found migration/spillover of crashes to be unlikely (*69*).

Overall, the advantages of rumble strips are generally accepted to outweigh the disadvantages (*70*,*69*):

- Rumble strip installation costs are low
- There is no noticeable degradation of pavement due to rumble strips
- Rumble strips require little or no maintenance
- Rumble strips are effective in snow and icy conditions and may act as a guide in inclement weather for truck drivers

FHWA Office of Safety’s extensive website regarding rumble strips is a valuable resource (http://safety.fhwa.dot.gov/programs/rumble.htm). New research is beginning under NCHRP 17-32, which may provide additional insight into rumble strip applications.

Based on the literature review in the following sections, there is a need to conduct research to quantify the safety effect of the following elements of rumble strips:

- Various traffic volume ranges on all road types
- Potential influence of different shoulder widths and lane widths
- Potential influence of different strip dimensions or types; at this time there is no indication that different dimensions or types have an effect on safety
- Motorcycles, pedestrians, and cyclists in terms of crash experience

The following sections discuss the safety impact of shoulder, centerline, and transverse rumble strips on roadway segments. Mid-lane and edgeline rumble strips may be included in future editions of the HSM.

3.2.3.1. Shoulder Rumble Strips

Shoulder rumble strips are defined by the FHWA as “a longitudinal design feature installed on a paved roadway shoulder near the travel lane. It is made of a series of indented or raised elements intended to alert inattentive drivers through vibration and sound that their vehicles have left the travel lane. On divided highways, they are typically installed on the median side of the roadway as well as on the outside (right) shoulder” (*71*).

The target crash type for shoulder rumble strips is typically single-vehicle run-off-road (SV ROR); however there is discussion that there may be benefits for head-on crashes as well.

For example, if a driver leaves the roadway (to the right) and overcompensates while trying to recover control of vehicle, the driver may head into the opposing direction of traffic (*43*). Shoulder rumble strips may reduce head-on crashes results from such a scenario by reducing the likelihood that the driver leaves the roadway.

Shoulder rumble strips have been implemented extensively on freeways, and are being implemented more commonly on two-lane and multi-lane rural roads. The intent is to alert the driver of an errant vehicle, using sound and vibration, that they are leaving or are about to leave the roadway.

The reader is directed to the Technical Advisory on Shoulder Rumble Strips issued by the FHWA, which can be found on-line at http://www.fhwa.dot.gov/legsregs/directives/techadvs/t504035.htm (*71*). This technical advisory contains the recommendation that rumble strips are not to be placed on shoulders used by bicyclists "unless there is a minimum clear path of 1 ft (0.3 m) from the rumble strip to the traveled way, 4 ft (1.2 m) from the rumble strip to the outside edge of the paved shoulder, or 5 ft (1.5 m) to adjacent guardrail, curb or other obstacle". This is in agreement with the 1999 American Association of State Highway and Transportation Officials (AASHTO) Guide for the Development of Bicycle Facilities. Other details regarding the accommodation of bicyclists can be found in the Technical Advisory.

The reader is directed to NCHRP Report 500 Volume 6 for additional discussion of implementation issues such as noise, motorcyclists, and winter maintenance (*16*).

The reader is also referred to the Science Applications International Corporation (SAIC) "Synthesis of Shoulder Rumble Strip Practices and Policies" which includes a review of shoulder rumble strip studies, motorist and bicyclist perceptions, results of nationwide surveys conducted in 2000, and a comparison of policies, practices, and alternative designs (*72*).

This section discusses the safety effect of shoulder rumble strips on rural multi-lane highways, including freeways; no conclusive safety studies were found for rural two-lane roads or urban and suburban arterials.

Shoulder widening in conjunction with shoulder rumble strip installation on rural multi-lane highways, including freeways is also included in this subsection. Again, no conclusive safety studies were found for this treatment on rural two-lane roads or urban and suburban arterials.

A brief discussion of the impact of shoulder rumble strips on motorcycles, pedestrians, and cyclists is also included here. Section 3.3 provides additional discussion of pedestrian and bicyclist considerations.

In future editions, this section may cover the safety effect of shoulder rumble strips on all road classes, at different traffic volume ranges; with varying shoulder width, lane width; for different rumble strip dimensions, types, and patterns (milled, rolled, formed, which require different times to construct and open to the traffic), etc. The safety impact on motorcycles, pedestrians, and cyclists may be quantified.

Exhibit 3-93: Resources examined to investigate the safety effect of shoulder rumble strips

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-32 "Guidance for the Design and Application of Shoulder and Centerline Rumble Strips" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-32	On-going project.	Results not available.
(*73*) (Carrasco, O., McFadden, J., and Chandhok, P., "Evaluation of the Effectiveness of Shoulder Rumble Strips on Rural Multi-lane Divided Highways In Minnesota." Washington D.C., 83rd Transportation Research Board Annual Meeting, (2004))	The study examined the safety effects of milled-in shoulder rumble strips on rural multi-lane divided highways at 23 sites and eight comparison sites in Minnesota, from 1991 to 1998. Also summarizes some previous results by other researchers.	Added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Strategy 15.2 A4 Shoulder rumble strips on horizontal curves.	No additional safety information provided (given in ROR guide) – not added to synthesis.
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Strategy 12.1 A3 Incorporate rumble strips into new and existing roadways. However, no safety effect information is given.	No safety information provided – not added to synthesis.
(*16*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The study focuses on 3 objectives to prevent vehicles from leaving the road. Synthesis of existing safety knowledge, with additional information on potential difficulties, implementation, and costs.	Safety effect noted by 3 other studies are provided – added to synthesis.
(*68*) (Torbic, D. J., Elefteriadou, L., and El-Gindy, M., "Development of More Bicycle-Friendly Rumble Strip Configurations." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	The study evaluated rumble strip patterns on non-freeway roads to establish which were the most effective for motorists and the friendliest for bicyclists. Tests were performed using simulator models; field tests were then performed with different bicycles, speeds, approach angles, and bicyclists. Motor vehicle testing was also conducted.	Suggested by NCHRP 17-18(4). No quantification of safety effect. However, two recommended patterns for bicyclists are added to HSM content.
(Transportation Association of Canada, "Best Practices for the Implementation of Shoulder and Centreline Rumble Strips." Ottawa, Ontario, Canada, Transportation Association of Canada, (2001))	The purpose of this document is to provide highway agencies with a summary of current practices to assist these agencies in the development of local guidelines and policies.	No additional safety information provided (given in other refs) – not added to synthesis.
(*74*) (Hanley, K. E., Gibby, A. R., and Ferrara, T. C., "Analysis of Accident Reduction Factors on California State Highways." Transportation Research Record, No. 1717, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 37-45.)	The study reviewed rumble strips, shoulders (widening), superelevation, horizontal curves and wet pavement treatments. Used Bayesian Estimation of Accidents in Transportation Studies software; before and after analysis with comparison groups. In all cases, shoulders on freeways were widened in conjunction with shoulder rumble strips.	Suggested by NCHRP 17-18(4). Limited to California data. Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways.	Limited quantitative information. Not added to synthesis.
(*69*) (Griffith, M. S., "Safety Evaluation of Rolled-In Continuous Shoulder Rumble Strips Installed on Freeways." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999))	The study examined the safety effects of continuous shoulder rumble strips using a before-after approach at 63 sites in Illinois and 28 sites in California.	Added to synthesis.
Moeur, C. Richard. Rumble Strip Gap Study. Final Report, May 1999.	This study examines the effect of placing gaps in rumble strips to allow bicycle to traverse smoothly. There was no mention of safety in this paper.	Not added to synthesis.
(*70*) (Perrillo, K., "The Effectiveness and Use of Continuous Shoulder Rumble Strips." Albany, N.Y., Federal Highway Administration, (1998))	Background of shoulder rumble strips, including discussion of possible negative impacts. Before/after crash data studied on New York Thruway.	Suggested by NCHRP 17-18(4). Results added to synthesis.
(Hickey Jr., J. J., "Shoulder Rumble Strip Effectiveness: Drift-off-Road Accident Reductions on the Pennsylvania Turnpike." Washington, D.C., 76th Transportation Research Board Annual Meeting, (1997))	The study examined the safety effects of Sonic Nap Alert Pattern in Pennsylvania. It is a follow up to the study done by Wood (1984). Studied reportable accidents (those involving fatality, injury or vehicle damage requiring towing). Drift off road (DOR) accidents include single vehicles striking objects off the right side of the roadway where SNAP was installed, and did not result from mechanical default of blowout.	Suggested by NCHRP 17-18(4). Results already added to synthesis as cited in Carrasco 2004.
(Harwood, D. W., "NCHRP Synthesis of Highway Practice Report 191: Use of Rumble Strips to Enhance Safety." Washington, D.C., Transportation Research Board, National Research Council, (1993))	Synthesis of the application of rumble strips to enhance highway safety, including operations, potential adverse effects, design and installation specifications, estimated cost and service life.	Limited quantitative information. Not added to synthesis.
(Agent, K. R. and Creasey, F. T., "Delineation of Horizontal Curves." UKTRP-86-4, Frankfort, Ky., Kentucky Transportation Cabinet, (1986))	Study of various delineation methods including chevrons, post mounted delineators, raised pavement markers, and transverse rumble strips in combination to enhance safety of horizontal curves. Simple before-after study of 4 sites.	No shoulder rumble strips. Added to transverse rumble strips section.
(Ligon, C. M., Carter, E. C., Joost, D. B., and Wolman, W. W., "Effects of Shoulder Textured Treatment on Safety." FHWA/RD-85/027, Washington, D.C., Federal Highway Administration, (1985))	The objective of the study was to determine the safety effects of shoulder textured treatments in reducing run-off-the road accidents on high volume rural freeways. The study compared 24 textured shoulder sites with corresponding control sections.	Suggested by NCHRP 17-18(4). Results already added to synthesis as cited in Carrasco 2004.

DOCUMENT	DESCRIPTION	COMMENT
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	The chapter discusses the relationship between accidents and cross sectional elements	No relevant information. Not added to synthesis.

The effectiveness of shoulder rumble strips has been quantified for freeways and rural multi-lane divided roadways. No studies of effectiveness for rural two-lane highways were found. Volume ranges are provided here where available. All studies added to the synthesis did not consider or did not provide data on shoulder width, lane width, dimensions of strips, or different types (milled, rolled, and formed).

The impact of shoulder rumble strips on motorcycles, pedestrians, or cyclists has not been quantified in terms of crash experience; however, surrogate measures and qualitative information are provided in several studies, and summarized at the end of this section.

Treatment: Install continuous shoulder rumble strips

Rural two-lane roads; Urban and suburban arterials; Expressways

No studies found.

Rural divided multi-lane highways; Freeways

Griffith (1999) studied continuous rolled-in shoulder rumble strips on urban and rural freeways in Illinois and California (*69*). It is not clear from the study if rumble strips were applied to all 4 shoulders of the freeway, but it is likely. The traffic volumes and speed limits of the study areas were not provided in the paper. The results of the study based on the Illinois data are summarized in Exhibit 3-94. These results were assigned a medium-high rating. The index of effectiveness is as stated by Griffith; the standard error is based on the standard deviations given by the author, adjusted by a method correction factor of 1.8 based on a medium-high rating for this study.

Griffith also notes that there is no evidence that SRS cause an increase in multi-vehicle accidents within the boundaries of the treatment area (i.e., no negative effect by SRS); also indicates no positive effect of SRS on multi-vehicle accidents (pg 13, (*69*)).

Carrasco et al. (2004) studied continuous milled-in shoulder rumble strips on all four shoulders with varying designs on rural multi-lane divided roads. The road segments studied had a volume range of approximately 2,000 to 50,000 veh/day, and posted speeds of 55 to 70 mph (88 to 112 km/h). The results of the study are summarized in Exhibit 3-94. This study was rated medium-low; the MCF of 2.2 was applied to the s ideal calculated based on the number of before crashes and the ratio of before/after duration to reach an estimate of the standard error (*73*).

Perillo (1998) investigated continuous milled-in shoulder rumble strips on all four shoulders of New York Thruways (multi-lane divided), focusing on selected SV ROR crashes with certain causes, including alcohol, drugs, inattention, inexperience, fatigue, illness, distraction, and glare. This study was considered of low quality (simple before/after, one year data before, one year data after) and a method correction factor of 3 (low rating) was applied to reach an estimate of standard error. The posted speed limit and traffic volumes were not provided in the report. The safety effects are summarized in Exhibit 3-94. Note that the magnitude of this AMF is quite large, likely due to the very specific crash type; the standard error is low due to the large number of crashes included in the study (*70*).

Exhibit 3-94: Safety effectiveness of shoulder rumble strips on rural multi-lane highways, including freeways

Author, date	Treatment/ Element	Setting	Road type	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Carrasco et al., 2004	Continuous milled-in shoulder rumble strips on all four shoulders with varying designs	Rural	Multi-lane divided	All types, all severities	0.84	0.13
Carrasco et al., 2004	Continuous milled-in shoulder rumble strips on all four shoulders with varying designs	Rural	Multi-lane divided	All types, injury	0.83	0.19
Carrasco et al., 2004	Continuous milled-in shoulder rumble strips on all four shoulders with varying designs	Rural	Multi-lane divided	All SV ROR, all severities	0.90	0.25
Carrasco et al., 2004	Continuous milled-in shoulder rumble strips on all four shoulders with varying designs	Rural	Multi-lane divided	All SV ROR, injury	0.78	0.33
Perillo, 1998	Continuous milled-in shoulder rumble strips on all four shoulders	Unknown	Thruway (multi-lane divided)	Selected SV ROR, all severities	0.21	0.07
Griffith, 1999	Continuous rolled-in shoulder rumble strips	Urban and Rural	Freeway	All SV ROR, all severities	0.82	0.12
Griffith, 1999	Continuous rolled-in shoulder rumble strips	Urban and Rural	Freeway	All SV ROR, injury	0.87	0.21
Griffith, 1999	Continuous rolled-in shoulder rumble strips	Rural	Freeway	All SV ROR, all severities	0.79	0.18
Griffith, 1999	Continuous rolled-in shoulder rumble strips	Rural	Freeway	All SV ROR, injury	0.93	0.28

Notes:

Griffith, 1999: Setting of urban and rural indicates rural data combined with urban data for analysis. Setting of rural is a subset of combined urban and rural data.

Perrillo, 1998: selected SV ROR crashes with certain causes, including alcohol, drugs, inattention, inexperience, fatigue, illness, distraction, and glare.

Treatment: Install continuous shoulder rumble strips and wider shoulders

Rural two-lane roads; **Rural multi-lane highways; Urban and suburban arterials; Expressways**

No studies found.

Freeways

Hanley et al. computed the safety effect of shoulder widening in conjunction with shoulder rumble strip installation on freeways in California. The posted speed limit and traffic volumes were not provided in the report. The ideal standard error was estimated by dividing the estimated percent reduction in accidents by the t-test values provided by Hanley et al. This study was considered of medium-high quality and an MCF of 1.8 was applied to reach an estimate of standard error. The safety effects found are summarized in Exhibit 3-95 (*74*).

Exhibit 3-95: Safety effectiveness of shoulder rumble strips in conjunction with shoulder widening on freeways (74)

Author, date	Treatment/ Element	Setting	Road type	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hanley et al, 2000	Shoulder widening with shoulder rumble strip installation	Unknown	Freeway	All types, all severities	0.81	0.20
Hanley et al, 2000	Shoulder widening with shoulder rumble strip installation	Unknown	Freeway	Drift-off-road, all severities	0.87	0.24

Urban and suburban arterials

No studies found.

Discussion: Impact of shoulder rumble strips on motorcycles, pedestrians, and cyclists

According to NCHRP Report 500 Volume 6, experience has shown that potential difficulties for SRS (including snow removal, drainage, maintenance, noise, motorcycles) can be addressed or dismissed through sensible policies and targeted application. Practitioners may wish to consider the presence of bicyclist users when considering shoulder rumble strips. Three studies were conducted in Pennsylvania, California, Colorado to test bicycle and motor vehicle testing of various rumble strip designs and recommended compromise between designs that provide the most noise and vibration for motorists, and the most comfort for cyclists (*16*).

Torbic et al. evaluated rumble strip patterns on non-freeway roads to establish which were the most effective for motorists and the most friendly for bicyclists (*68*). The authors recommend two patterns:

1. 127 mm wide, 178 mm edge to edge between cuts, 10 mm deep for operating speed of 55 mph (88 km/h)
2. 127 mm wide, 178 mm edge to edge between cuts, 6.3mm deep for operating speed of 45 mph (72 km/h)

Torbic et al. provide detailed discussion on the evaluation process. Section 3.3 contains further discussion of cyclist accommodation.

In conclusion, the impact of shoulder rumble strips on pedestrians and cyclists have not been adequately quantified; the safety professional may wish to consider the presence of cyclists when considering the implementation of shoulder rumble strips. There are potential design alternatives that provide adequate warning to motorists while not adversely affecting bicycle operations. There is no quantified negative impact on motorcyclists.

3.2.3.2. Centerline Rumble Strips

Centerline rumble strips can be implemented on undivided roadways to reduce opposing-direction crashes. Target crashes for centerline rumble strips include head-on and opposite-direction sideswipe, with a secondary target crash of run-off-road-to-the-left.

Torbic et al. state, “Centerline rumble strips are installed primarily to reduce head-on and sideswipe crashes along undivided roadways. Their primary function is to alert drowsy or otherwise inattentive drivers that their vehicles are encroaching upon the opposing lane through tactile and auditory stimulation.” (*43*)

Centerline rumble strips may somewhat reduce risky passing or other maneuvers, but this is not the primary intent of their application. As noted by Torbic et al., “centerline rumble strips may also discourage drivers from cutting across the inside of a curve” (*43*).

Currently, there are no national guidelines for the application of centerline rumble strips; the FHWA Rumble Strips website is a valuable source of current information (http://safety.fhwa.dot.gov/roadway_dept/rumble/index.htm).

This section discusses the safety effects of the implementation of centerline rumble strips. Centerline pavement markings (paint or raised thermoplastic stripes) are also discussed in this section.

General issues with rumble strips, such as noise, maintenance, driver reaction, bicyclists, and motorcyclists are discussed above in Section 3.2.3.

Exhibit 3-96: Resources examined to investigate the safety effect of centerline rumble strips on undivided roadways

DOCUMENT	DESCRIPTION	COMMENT
NCHRP 34-01 synthesis (Gene Russell, Margaret Rys)	Project is on-going	Results not available.
(*76*) Transportation Association of Canada “Centreline Rumble Strips Synthesis”	Synthesis of practices and research.	Some qualitative information added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Noyce, D. A. and Elango, V. V., "Safety Evaluation of Centerline Rumble Strips: A Crash and Driver Behavior Analysis." Washington, D.C., 83rd Annual Meeting of the Transportation Research Board, (2004))	The study evaluated the safety impact of centerline rumble strips on undivided roadways in Massachusetts. Driver behavior was evaluated using a full-scale driving simulator.	Insufficient data to calculate t and s. Not added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report focuses on strategies to prevent the crash types prevalent on horizontal curves.	No additional quantitative information. Not added to synthesis.
(*75*) (Persaud, B. N., Retting, R. A., and Lyon, C., "Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads." Arlington, Va., Insurance Institute for Highway Safety, (2003))	The study examined 210 miles of two-lane rural roads in seven states before and after the installation of centerline rumble strips (California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington).	Added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The report focuses on strategies to prevent head-on crashes.	Only quantitative results are from Delaware, and superseded by Persaud et al (2003). Not added to synthesis.
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The report focuses on strategies to prevent crashes involving heavy trucks.	No additional quantitative information provided that wasn't in NCHRP 500 V7. Not added to synthesis.
(Outcalt, W., "Centerline Rumble Strips." CDOT-DTD-R-2001-8, Denver, Colorado Department of Transportation, (2001))	Evaluation of centerline rumble strips on two-lane mountain highway.	Colorado is included in Persaud et al, 2003. Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways.	Reviewed in NCHRP 500 V4 [Neuman et al (2003)]. Not added to synthesis.
(Perrillo, K., "The Effectiveness and Use of Continuous Shoulder Rumble Strips." Albany, N.Y., Federal Highway Administration, (1998))	Limited information on centerline rumble strips; summarizes CLRS findings in Delaware.	Only quantitative results are from Delaware, and superseded by Persaud et al (2003). Not added to synthesis.
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	The chapter discusses the relationship between accidents and cross sectional elements.	Use in transverse rumble strip section. No use for centerline rumble strips. Not added to synthesis.

Information on the effectiveness of centerline rumble strips is limited. Few studies were found with sufficient data to determine an index of effectiveness.

Treatment: Install centerline rumble strips

Rural two-lane roads

Persaud et al. (2003) found that centerline rumble strips on two-lane rural roads had a positive effect on safety, as summarized in Exhibit 3-97. This study was based on various centerline rumble strip designs in seven states (California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington); the average segment length in the study was 2 miles, with traffic volumes from 5,000 to 22,000 veh/day, and included both horizontal curves and tangent sections (*75*).

Persaud et al. provided the 95% confidence intervals of the results, which were used to compute standard errors of the estimates, and a method correction factor of 1.8 (EB medium-high rating) was applied. Note that the data set used in this study was not homogeneous; elements such as rumble strip types and designs, roadway geometry, traffic volumes, environmental conditions varied in the data set. In addition, in some cases other treatments were applied in conjunction with the centerline rumble strips (e.g., raised pavement markers, signs requiring daytime headlight), and the potential effects of additional treatments were not studied. Persaud et al. note that the small sample sizes that result from disaggregating the data did not permit studying the safety effects of varying elements.

Exhibit 3-97: Safety effectiveness of centerline rumble strips on rural two-lane roads (75)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Persaud et al, 2003	Centerline rumble strips	Rural	Two-lane, 5,000 to 22,000 veh/day	All types, all severities	0.86	0.05
Persaud et al, 2003	Centerline rumble strips	Rural	Two-lane, 5,000 to 22,000 veh/day	All types, injury	0.85	0.09
Persaud et al, 2003	Centerline rumble strips	Rural	Two-lane, 5,000 to 22,000 veh/day	Frontal and opposing-direction sideswipe, all severities	0.79	0.14
Persaud et al, 2003	Centerline rumble strips	Rural	Two-lane, 5,000 to 22,000 veh/day	Frontal and opposing-direction sideswipe, injury	0.75	0.18

Torbic et al. note "It is possible that the use of a centerline rumble strip might have some negative operational effects by inhibiting passing maneuvers (due to the look and noise of the strips). However, states currently using these rumble strips have not reported such problems" (pg v-7 (*43*)). No studies were found that measure an effect on passing behavior.

Based on a synthesis of current practices, there is some debate about the effect of painting the centerline on top of centerline rumble strips. According to some studies, retroreflectivity of the centerline marking is not reduced if the line is painted on top of the rumble strip; it may even be enhanced (e.g., Alberta, Michigan, Texas). Other studies conclude that there may be a reduction in the visibility of the centerline marking, particularly if some debris settles in the rumble strip groove (e.g., snow, salt, sand) (e.g., Massachusetts, Minnesota, Saskatchewan). None of the studies provide conclusive results (*76*).

As an alternative, it is current practice by some highway agencies to paint the centerline on either side of the centerline rumble strip (e.g., Massachusetts), creating a narrow flush median. Other jurisdictions install the centerline rumble strips on either side of the centerline pavement marking (e.g., Minnesota) (*76*). The safety impact of these alternatives has not been reported.

Based on the review of current practices, it is evident that CLRS are generally not placed through intersections or at access points (*76*).

Rural multi-lane highways; Urban and suburban arterials

No studies found.

Discussion: Install centerline raised thermoplastic stripes

This treatment is discussed in NCHRP Report 500 Volume 7 (Strategy 18.1 A2 – Profiled Thermoplastic Stripes for Centerline). This treatment has been implemented on two-lane roads by two states, California and Texas; however, no formal safety effect evaluation has been conducted to date. This treatment is likely to be applied only in climates that rarely experience snow fall, as snow removal equipment may damage the raised thermoplastic stripes.

Rural multi-lane highways; Urban and suburban arterials

No studies found.

3.2.3.3. Transverse Rumble Strips

Transverse rumble strips (also known as "in-lane" rumble strips or "rumble strips in the traveled way") are applied to the road surface perpendicular to the direction of travel, across the travel lane. The intent is for each vehicle to encounter the transverse rumble strips to warn them of an upcoming change in the roadway. Transverse rumble strips have been used as part of traffic calming schemes, in work zones, in advance of toll plazas, and in advance of intersections, railroad-highway grade crossings, bridges and tunnels.

There are concerns that drivers will cross into opposing lanes of traffic in order to avoid contacting transverse rumble strips. Similar to other rumble strips, there are also concerns for noise, motorcyclists, bicyclists, and maintenance, as previously discussed in Section 3.2.3.

Currently, there are no national guidelines for the application of transverse rumble strips; the FHWA Rumble Strips website is a valuable source of current information (http://safety.fhwa.dot.gov/roadway_dept/rumble/index.htm).

Other sections of the HSM contain information on the use of transverse rumble strips in advance of intersections (Section 4.2.8), railroad-highway grade crossings (Section 6.1), bridges (Section 6.3), tunnels (Section 6.4), or toll plazas (Section 6.17). Transverse rumble strips applied for speed reduction purposes (including in advance of speed transition zones) on segments are discussed in Section 3.2.7 and applications at mid-block pedestrian crossings or in school zones are discussed in Section 3.3.

Exhibit 3-98: Resources examined to investigate the safety effect of transverse rumble strips on segments

DOCUMENT	DESCRIPTION	COMMENT
(*77*) Transportation Association of Canada "Best Practice Guidelines for the Design and Application of Transverse Rumble Strips"	On-going project. Not yet published. Reviewed Final Draft Report.	Added to synthesis.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Overview of current knowledge on effects of road safety measures.	Transverse rumble strips in advance of intersections for reducing speed. Not added to synthesis.
(Smiley, A., "Rumble Strip Impact on Speed Variance." (2004))	The paper discusses the impact on drivers of transverse rumble strips, particularly regarding speed, speed variance, accidents, and design on intersection approaches.	No AMFs. No relevant information for transverse rumble strips on segments. Not added to synthesis.
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Strategy 12.1 A3 Incorporate rumble strips into new and existing roadways. However, no safety effect information is given.	No information on transverse rumble strips. Not added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	The report review and brings together available evidence on the safety impact of traffic operations. The study focuses on traffic operations and control strategies and providing useful information.	Transverse rumble strips in advance of rural intersections. Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways.	No accident data for transverse rumble strips. Not added to synthesis.
(Perrillo, K., "The Effectiveness and Use of Continuous Shoulder Rumble Strips." Albany, N.Y., Federal Highway Administration, (1998))	Primarily focused on shoulder rumble strips. Limited discussion of transverse and centerline applications.	No quantitative results for transverse, only shoulder. Used in SRS section. Not added to synthesis.
(*78*) (Harwood, D. W., "NCHRP Synthesis of Highway Practice Report 191: Use of Rumble Strips to Enhance Safety." Washington, D.C., Transportation Research Board, National Research Council, (1993))	Synthesis of rumble strip applications, operational and safety effectiveness, design, and other issues.	Qualitative discussion added to synthesis. No AMFs for segment application.
(*64*) (Agent, K. R. and Creasey, F. T., "Delineation of Horizontal Curves." UKTRP-86-4, Frankfort, Ky., Kentucky Transportation Cabinet, (1986))	Study of various delineation methods including chevrons, post mounted delineators, raised pavement markers, and transverse rumble strips in combination to enhance safety of horizontal curves. Simple before-after study of 4 sites.	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	This chapter discusses cross section and pavement surface elements at segments and intersections.	Transverse rumble strips in advance of rural intersections. Not added to synthesis.

The bulk of the research reviewed discusses transverse rumble strips applied in advance of intersections, and is not added to the discussion here.

The following general findings are based on a synthesis of practices and extensive literature review performed for the Transportation Association of Canada (*77*). Although inconclusive, the authors of that paper note several key, and often subtle, findings:

- Speed reduction effect ranges from minimal to no effect; studies are inconclusive
- Effect of transverse rumble strips diminishes with decreasing average operating speed, thus transverse rumble strips has a greater effect in areas with higher speeds/posted speed limits
- Transverse rumble strips, as a warning device, maintain effectiveness over time for familiar and even more so for unfamiliar drivers
- With the installation of transverse rumble strips across the full lane width, drivers brake more and earlier, which could result in greater compliance of traffic control devices ahead. Thus, transverse rumble strips should always be used in conjunction with other traffic control measures, such as warning beacons, additional signage, etc, to assist the driver to interpret the warning message.
- Transverse rumble strips with a depth less than 0.24 inches (6 mm) are largely ineffective
- Effect of transverse rumble strips on speed and pedestrian accidents at pedestrian crossings was inconclusive
- Transverse rumble strips are effective in reducing injury crashes when specifically analyzing target crashes (i.e., crashes that are the result of failing to obey the traffic control device or failing to adapt to new conditions at the specific location)
- Transverse rumble strips work best when they are unexpected and therefore converging patterns are not recommended. Converging patterns can create a lull effect and therefore fail in raising awareness of the driver’s surroundings
- Intermittent (as opposed to continuous), full-lane (as opposed to “partial’ or “wheel-width”) transverse rumble strips are more effective and less likely to produce undesirable driver behavior such as lane deviation and inconsistent and/or hard braking maneuvers
- Painted transverse rumble strips have not been proven more effective, and they contribute to higher installation and maintenance costs
- Transverse rumble strips should be used sparingly and selectively because over-application of transverse rumble strips may create driver expectation issues and may desensitize drivers to the audible and vibratory effect

Treatment: Install transverse rumble strips and raised pavement markers on approach to horizontal curves

Rural two-lane roads

Agent and Creasey (*64*) investigated the use of transverse markings, rumble strips and raised pavement markers to delineate horizontal curves on two-lane, undivided rural roads. The type and design of the rumble strips and raised pavement markers, and the volumes and posted speeds at the study sites were not specified in the paper. Although the traffic volumes were not reported, it is expected that they were likely to be in the lower range (AADT < 5,000 veh/day).

This study was considered to be of low quality and the standard error values have been multiplied with a method correction factor of 3.0 accordingly. The resulting standard errors are quite large, primarily due to the small number of crashes in the study, and instill little confidence in the indices of effectiveness (Exhibit 3-99).

Exhibit 3-99: Safety effectiveness of transverse rumble strips and raised pavement markers on approach to horizontal curves on rural two-lane roads

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing RPMs and background/ directional markings on horizontal curves	Rural	Two-lane undivided, volume not reported	Single-vehicle run-off-road (SV ROR), Injury Accidents	0.94	0.49
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	All types, all severities	1.10	1.26
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	Wet accidents, all severities	0.91	1.16
Agent and Creasey, 1986	Transverse rumble strips, RPMs, transverse markings*	Rural	Two-lane, horizontal curve, volume not reported	Nighttime accidents, all severities	0.83	1.88
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	All types, all severities	0.47	0.50
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	Wet accidents, all severities	0.51	0.55
Agent and Creasey, 1986	Transverse rumble strips, RPMs	Rural	Two-lane, horizontal curve, volume not reported	Nighttime accidents, all severities	0.36	1.37

NOTE: *For this site, the westbound direction had transverse rumble strips and RPMs while the eastbound direction had transverse pavement markings and RPMs

Harwood discusses the application of rumble strips in advance of horizontal curves on segments, used by a few agencies, particularly curves with advisory speed limits or at the end of long tangent sections ((*78*), pg 6). "Rumble strip usage on the approach to a horizontal curve is intended to reduce skidding or run-off-road accidents involving drivers who do not see the curve or who enter the curve at too high a speed" ((*78*), pg 6).

Rural multi-lane highways; **Freeways; Expressways; Urban and suburban arterials**

No studies found.

Discussion: Install transverse rumble strips on approach to lane drop

According to Harwood, a few highway agencies have applied transverse rumble strips on freeways in advance of the termination of a right or left lane on freeways (*78*). In this application, transverse rumble strips are placed in the lane that is ending to prompt drivers to merge into remaining lanes. No studies were found that provide AMFs for this treatment.

Discussion: Install transverse rumble strips at freeway termination

As reported by Harwood, some highway agencies have implemented transverse rumble strips in the traveled way at the end of a freeway where all freeway traffic is directed onto a conventional highway. No studies were found on the safety effect of this type of treatment.

3.2.3.4. Mid-lane Rumble Strips [Future Edition]

Mid-lane rumble strips are applied along the centre of a travel lane, parallel to the direction of travel. In future editions of the HSM, the safety effect of the implementation of such rumble strips may be discussed in this section. Potential resources are listed in Exhibit 3-100.

Exhibit 3-100: Potential resources on the relationship between mid-lane rumble strips and safety

DOCUMENT
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))

3.2.3.5. Edgeline Rumble Strips [Future Edition]

Edgeline or "lane line" rumble strips, also known as "rumble stripes" are applied between lanes of the same direction of travel. In future editions of the HSM, the safety effect of the implementation of such rumble strips may be discussed in this section. Potential resources are listed in Exhibit 3-101.

Exhibit 3-101: Potential resources on the relationship between edgeline rumble strips and safety

DOCUMENT
(J.K. Lindly and R.K. Wijesundera, "Evaluation of profiled pavement markings", University Transportation Center for Alabama, Submitted to Alabama Department of Transportation, UTCA Final Report 01465, Alabama DOT Research Project No. 930-506, November 13, 2003)

3.2.4. Passing Zones on Two-Lane Roads

A no-passing zone is established on a two-lane roadway wherever restricted sight distance makes overtaking and passing inappropriate. The passing maneuver on two-lane highways is demanding and potentially hazardous, as the passing vehicle must occupy the opposing lane of traffic to complete the maneuver. Sight distance may be restricted by horizontal curves or by crest vertical curves. Passing zones exist on two-lane roadways where no-passing zones are not warranted.

The passing maneuver is complex as it involves three moving vehicles (the passing vehicle, the passed vehicle and any oncoming vehicle) and the passing driver's dynamic interpretation of sight distance. Sight distance factors include change of grade, the length of the curve, the height above the ground of the driver's eye, and the height of the obstacle to be seen. Drivers must also have adequate stopping sight distance (SSD). SSD is determined by reaction time, the speed of vehicle, and the tire-pavement coefficient of friction (*50*).

The MUTCD provides general guidance for road markings for passing zones and no-passing zones on two-lane roadways (*50*). There are three possibilities:

- Two-direction passing zone markings - a normal broken yellow line. Crossing the centerline markings with care when passing is permitted for traffic traveling in either direction;
- One-direction no-passing zone markings - a normal broken yellow line and a normal solid yellow line. Crossing the centerline markings with care when passing is permitted for the traffic traveling adjacent to the broken line, but is prohibited for traffic traveling adjacent to the solid line.
- Two-direction no-passing zone markings - two normal solid yellow lines. Crossing the centerline markings for passing is prohibited for traffic traveling in either direction.

A "DO NOT PASS" sign may be used in addition to pavement markings to emphasize the restriction on passing. A "NO PASSING ZONE" sign may also be installed on the left side of the roadway at the beginning of no-passing zones identified by pavement markings, "DO NOT PASS" signs or both (*50*).

The minimum length of no-passing zones, and the minimum length between adjacent no-passing zones (passing zone frequency) are not clearly established (and are currently being investigated in NCHRP Project 20-5 (Synthesis 36-06), expected completion date of April 2006). The length of a no-passing zone will vary with the sight distance, volume, delays, speed, acceleration rate, and directional split of the traffic. Passing zone frequency varies with physical and cost limitations.

This section examines the safety effect of using passing zones to permit passing on two-lane roads where appropriate. Passing lanes are discussed in Chapter 6.

Exhibit 3-102: Resources examined to investigate the relationship between passing zones and safety

DOCUMENT	DESCRIPTION	COMMENT
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, UK, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	No relevant information. Not added to synthesis
(Hassan, Y. and Easa, S. M., "Design Considerations of Sight Distance Red Zones on Crest Curves." Journal of Transportation Engineering, No. July/August, (1998) pp. 343-351.)	The study used 3D analysis to investigate the introduction of a horizontal curve at or near the top of a crest vertical curve. The relevance to safety is suggested, but not directly investigated.	No AMFs. Not added to synthesis.
(*79*) (Glennon, J. C., "Accident Effects of Centerline Markings on Low-Volume Rural Roads." Transportation Research Record 1027, (1985) pp. 7-13.)	The study's objective was to verify or modify NCHRP warrants for centerline and no-passing zones on low volume rural roads.	Very limited qualitative and quantitative information. Added to synthesis.
(Harwood, D. W. and Glennon, J. C, "Framework for Design and Operation of Passing Zones on Two-Lane Highways." Transportation Research Record, No. 601, (1977) pp. 45-50.)	The authors noted the need to develop design and marking standards that consider both passing sight distance and passing zone length.	No safety studies. No AMFs. Not added to synthesis.
Jones, "An Evaluation of the Safety and Utilization of Short Passing Sections"	Identified by Hassan as applicable study	Suggested by NCHRP 17-18(4). Unable to obtain a copy. Not pursued due to age of study (1970).

Glennon examined low-volume two-lane rural roads with 10 to 11 ft lanes where no-passing zone markings were added to roads previously marked with a dashed centerline only or a dashed centerline with edgelines (*79*). Glennon concludes that the application of centerline markings on previously unmarked, low volume, two-lane rural roads appears to have a negative impact on injury crashes. Glennon goes on to say that "despite this seemingly negative result", there is a potential safety benefit from applying centerline markings to "wider roads that carry higher traffic volumes … both for adding centerline and no-passing zone markings to previously unmarked roads and for adding no-passing zone marking to roads previously marked with only a dashed centerline". Insufficient information was reported to determine an index of effectiveness and standard error for the study's findings.

The safety effects of using passing zones to permit passing on two-lane roads have scarcely been investigated. No studies that investigated and compared crashes in passing zones and crashes in no-passing zones were found.

3.2.5. Speed Limits [Future Edition]

In future editions of the HSM, the safety effects of speed limits may be discussed here. This section may include posted, variable and differential speed limits, operational speeds, and design speeds if available. Potential resources are listed in Exhibit 3-103.

Exhibit 3-103: Potential resources on the relationship between speed limits and safety

DOCUMENT
(Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))
(Kockelman, K., Lave, C., and Charles River Associates Inc., "Safety Impacts and Other Implications of Raised Speed Limits on High-Speed Roads." NCHRP Project 17-23 Interim Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2003))
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))
(Alicandri, E., Warren, D.L., "Managing Speed" Public Roads Vol. 66 No. 4 (2003))
(Weiss, A. and Schifer, J. L., "Assessment of Variable Speed Limit Implementation Issues." NCHRP 3-59, Washington, D.C., Transportation Research Board, National Research Council, (2001))

3.2.6. Traffic Calming

The objective of traffic calming is usually to reduce speed or traffic volume, in order to reduce conflicts between local traffic and through traffic, make it easier for pedestrians to cross the road and reduce traffic noise. Traffic calming can be applied both in residential areas and on roads that have commercial roadside development.

Traffic calming of main highways serving through traffic has been applied in many European towns, usually as an alternative to, or in addition to, the construction of bypasses. Following traffic calming, these highways are sometimes referred to as "environmental streets", since one of the purposes of traffic calming has been to provide a more pleasant environment for pedestrians and cyclists and encourage residents and shoppers to walk along the roads and stay more outdoors. To date, this concept does not seem to have gained a wide application in the United States. Hence, most of the studies that have evaluated the safety effects of traffic calming on roadway segments have been made in Europe.

Evidence from studies that have evaluated the safety effects of traffic calming will first be presented on streets with the application of several of the design elements listed above (lane narrowing, humps, parking bays, etc.). Then, evidence will be presented concerning the safety effects of specific treatments, in particular raised crosswalks, speed humps, and transverse rumble strips.

The main source of evaluation studies is the Handbook of Road Safety Measures (*8*). The studies referred to in that book have been updated by more recent studies that are easily available. An extensive literature search has not been performed.

Exhibit 3-104: Resources examined on the safety effect of traffic calming

DOCUMENT	DESCRIPTION	COMMENT
(Smiley, A., "Speed-Reducing Countermeasures." (2004))	Review of countermeasures, including pavement markings, medians, landscaping/side friction, signing, enforcement, and measures specific to rural isolated intersections	No AMFs. Not added to synthesis
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	A compilation of research, workshops, and actual demonstration of the guides by agencies provided for the resulting best practices summary for each individual safety emphasis area	No AMFs. Not added to synthesis
(8) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Overview of current knowledge on effects of road safety measures.	Transverse rumble strips in advance of intersections for reducing speed. Not added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	A synthesis of studies and research projects on the safety impacts of traffic operations and control strategies	No AMFs. Not added to synthesis
(Elvik, R., "Area-wide Urban Traffic Calming Schemes: A Meta-Analysis of Safety Effects." Accident Analysis and Prevention, Vol. 33, No. 3, Oxford, N.Y., Pergamon Press, (2001) pp. 327-336.)	A meta-analysis of 33 studies that evaluated the effect of traffic calming on safety	Suggested by NCHRP 17-18(4). Added to Chapter 7.
(Huang, H. F. and Cynecki, M. J., "The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior." FHWA-RD-00-104, McLean, Va., Federal Highway Administration, (2001))	Evaluated numerous traffic calming measures using before and after studies in 3 cities, and cross-sectional studies in 5 cities; employed surrogates (e.g., speeds and compliance)	Suggested by NCHRP 17-18(4). Uses surrogate measures for safety; not added to synthesis.
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Conducted a study of the safety benefits of providing marked or unmarked pedestrian crossings at various intersection types; information was pooled from the USA and Europe	No AMFs. Not added to synthesis.
(Wilbur Smith Associates, "Bicycle Boulevard Design Tools and Guidelines." Berkeley, Calif., City of Berkeley Planning and Development Department, (2000))	Review of the impacts of selected traffic calming devices on traffic, volume, and on collisions based on three individual sources	No AMFs. Not added to synthesis
(Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))	An independent report in a series of pedestrian safety synthesis reports to document pedestrian safety in other countries	No AMFs. Not added to synthesis.
(Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))	A compilation of the most relevant research from the United Kingdom; including a literature search, technical expertise, consultation with various academics and practitioners and a 5 year review of relevant literature from a variety of sources.	No AMFs. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Ewing, R., "Impacts of Traffic Calming." Transportation Quarterly, Vol. 55, No. 1, Washington, D.C, Eno Foundation for Transportation Inc., (2000) pp. 33-46.)	Summarizes the results of hundreds of before-and-after studies of traffic calming	Suggested by NCHRP 17-18(4). Duplicates report FHWA-RD-99-135. Not added to synthesis.
(Ewing, R. H., "Traffic Calming: State of the Practice." FHWA-RD-99-135, Washington, D.C., Federal Highway Administration, (1999))	Research of traffic calming measures and their inherent impacts on the immediate environment as well as the study of legal, emergency, and public effects	No AMFs. Not added to synthesis.
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))	A review of relationships that exist between vehicle travel speeds and resulting pedestrian injury using available literature and data sets	No AMFs. Not added to synthesis
(Garder, P., Leden, L., and Pulkkinen, U., "Measuring the Safety Effect of Raised Bicycle Crossings Using a New Research Methodology." Transportation Research Record 1636, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 64-70.)	Before and after study of raised urban bicycle crossings in Sweden	Suggested by NCHRP 17-18(4). Not added to synthesis. Used in the HSM bike intersection synthesis.
(Mertner, J. and Jorgensen, L., "Effects of Traffic Calming Schemes in Denmark." Transactions on the Built Environment, Vol. 33, Southampton, United Kingdom, WIT Press, (1998) pp. 213-223.)	Before and after study of traffic calming in Denmark, evaluated safety	Suggested by NCHRP 17-18(4). Uses surrogate measures, not added to synthesis.
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	Conducted a literature review and surveys of Canadian jurisdictions for the purpose of evaluating the contribution of non-enforcement measures to the overall approach to speed control	Uses surrogate measures, not added to synthesis.
(Zein, S. R., Geddes, E., Hemsing, S., and Johnson, M., "Safety Benefits of Traffic Calming." Transportation Research Record 1578, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 3-10.)	Conducted a study of the safety benefits of traffic calming at four sites in Vancouver; also reviewed 85 case studies from Europe, Australia and North America	Suggested by NCHRP 17-18(4). Reviewed by Elvik 2001. Too few data to be included in meta-analysis
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	A review incorporating a variety of studies including accident data, facility design guidelines, route designation criteria, and evaluations of facilities based on observational analysis accident data	No AMFs. Not added to synthesis.

The following thirteen studies, as reviewed by Elvik and Vaa (*8*), have been included in the synthesis of evidence for traffic calming on road segments (Exhibit 3-105).

Exhibit 3-106 lists studies that have evaluated the effects of speed humps, raised pedestrian crosswalks and transverse rumble strips on safety, and are included in this synthesis, as reviewed by Elvik and Vaa (*8*).

Exhibit 3-105: Studies included in synthesis of evidence of safety effects of traffic calming (8)

Study	Country	Design	Number of estimates
Borges et al 1985	Denmark	Simple before-after	9
Stølan 1988	Norway	Simple before-after	2
Angenendt 1991	Germany	Simple before-after	2
Freiholtz 1991	Sweden	Simple before-after	2
Baier et al 1992	Germany	Simple before-after	2
Schnüll and Lange 1992	Germany	Simple before-after	2
Aakjer Nielsen and Herrstedt 1993	Denmark	Before-after with comparison group	6
Herrstedt et al 1993	Denmark	Simple before-after	29
Engel and Andersen 1994	Denmark	Simple before-after	1
Wheeler and Taylor 1995	Great Britain	Simple before-after	6
Wheeler and Taylor 1999	Great Britain	Simple before-after	6
Grendstad et al 2003	Norway	Empirical Bayes before-after	1
Hirst et al 2004	Great Britain	Empirical Bayes before-after	1

Exhibit 3-106: Studies that have evaluated effects of speed humps, raised pedestrian crosswalks and transverse rumble strips (8)

Study	Country	Design	Number of estimates
Studies that have evaluated speed humps			
Baguley 1982	Great Britain	Before-after with comparison group	9
Blakstad and Giæver 1989	Norway	Case-control study	2
Giæver and Meland 1990	Norway	Before-after with comparison group	2
Webster 1993	Great Britain	Simple before-after	32
Webster and Mackie 1996	Great Britain	Simple before-after	1
ETSC 1996	Denmark	Simple before-after	10
Al-Masaeid 1997	Jordan	Before-after, matched comparison	1
Eriksson and Agustsson 1999	Denmark	Simple before-after	1
Ewing 1999	United States	Simple before-after	2
Agustsson 2001	Denmark	Simple before-after	1
Studies that have evaluated raised pedestrian crosswalks			
Engel and Thomsen 1983	Denmark	Simple before-after	2
Jones and Farmer 1988	Great Britain	Simple before-after	4
Downing et al 1993	Pakistan	Before-after with comparison group	2
Blakstad 1993	Norway	Simple before-after	2

Studies that have evaluated transverse rumble strips			
Kermit and Hein 1962	United States	Simple before-after	2
Owens 1967	United States	Simple before-after	2
Kermit 1968	United States	Simple before-after	1
Hoyt 1968	United States	Simple before-after	2
Bellis 1969	United States	Before-after, matched comparison	2
Illinois Div. of Highways 1970	United States	Simple before-after	1
Sumner and Shippey 1977	Great Britain	Simple before-after	1
Helliar-Symons 1981	Great Britain	Before-after with comparison group	4
Moore 1987	United States	Simple before-after	36
Virginia Dept. of Highways 1991	United States	Simple before-after	2
Webster and Layfield 1993	Great Britain	Simple before-after	12

Treatment: Apply several traffic calming measures to a road segment

Measures that are part of traffic calming typically include:

- Narrowing driving lanes, often by widening sidewalks
- Installing chokers or curb bulbs
- Using cobblestone in short sections of the road
- Providing raised crosswalks or speed humps
- Installing transverse rumble strips, usually at the start of the treated roadway segment
- Providing parking bays

A traffic calmed street is typically about 0.6 mi long (1 km), has two lanes and a very high access point density. Land use is usually mixed, with small shops and dwellings dominating. The speed limit before conversion is usually 31 or 37 mph (50 or 60 km/h).

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Not applicable.

Urban two-lane roads

In Europe (where the studies were performed), traffic calming is generally applied to two-lane highways and the speed limit is usually 31 or 37 mph (50 or 60 km/h). Land use is urban, often consisting of a mixture of shops and dwellings. Typical traffic volume (AADT) is 6,000 to 8,000 veh/day.

Thirteen studies have been identified, providing a total of 69 estimates of effect. Forty-five estimates of effect refer to injury accidents, 24 estimates of effect refer to property-damage-only accidents. Most of the studies are simple before-after studies that did not control for regression-to-the-mean or long-term trends. All these studies did, however, provide data on mean speed and traffic volume (AADT) before and after traffic calming. Only the two most recent studies have employed a full empirical Bayes (EB) design, controlling for regression-to-the-mean, long-term trends and local changes in traffic volume (i.e., changes that depart from the overall trend, whose effects are therefore not accounted for by means of a comparison group).

With respect to study quality, 61 of the estimates have been rated as low, 6 as medium low and 2 as high. The standard error has been adjusted by a method correction factor of 3 for low quality estimates of effect, 2.2 for medium low quality estimates of effect, and 1.2 for high quality estimates of effect.

Exhibit 3-107 provides summary estimates of the effects on accidents, employing a random-effects model of meta-analysis (*8*). Uncertainty in summary estimates is stated as the standard error. The estimates refer to all accidents occurring along the highway segments that have been converted.

Exhibit 3-107: Summary estimates of the effect on accidents of traffic calming (8)

Author, date	Treatment/ Element	Setting	Road type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Traffic calming	Urban	Two-lane, 6,000 to 8,000 veh/day	All types, all severities	0.680	0.078
Elvik and Vaa, 2004	Traffic calming	Urban	Two-lane, 6,000 to 8,000 veh/day	All types, injury	0.667	0.085
Elvik and Vaa, 2004	Traffic calming	Urban	Two-lane, 6,000 to 8,000 veh/day	All types, PDO	0.747	0.188
Elvik and Vaa, 2004	Traffic calming	Urban	Two-lane, 6,000 to 8,000 veh/day	All types, injury	0.672	0.094

All summary estimates of effect are close to each other, indicating that the number of accidents is reduced by about 30 percent. The effects on injury accidents appear to be somewhat larger than the effects on property-damage-only accidents.

The effects of traffic calming on accidents depend on the size of their effect on speed. Exhibit 3-108 summarises the relationship between the effect on speed and the effect on accidents for injury accidents. There were too few estimates to develop a similar relationship for property-damage-only accidents. Exhibit 3-108 is based on the same studies as those listed in Exhibit 3-105. For the traffic calmed streets included in this review, mean speed was reduced from an average of 55.7 km/h before conversion to 46.9 km/h after conversion.

Traffic calming does not seem to improve safety if speed is not reduced. If speed is reduced, there is an increasing reduction in the number of injury accidents as the reduction in mean speed increases. Many of the estimates in Exhibit 3-108 are likely to be confounded by regression-to-mean effects. Some of the estimates are based on few studies and are associated with large standard errors. The relationship between the size of the reduction in speed and the size of the reduction in accidents is nevertheless quite systematic, suggesting that the changes in the number of accidents are not fully attributable to the effects of confounding factors not controlled for.

Exhibit 3-108: Relationship between effect on speed and effect on injury accidents of traffic calming (8)

Change in mean speed	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
No change	1.562	0.857
Down 0-5% (mean –3.3%)	0.811	0.532
Down 5-10% (mean –7.1%)	0.678	0.371
Down 10-15% (mean –11.0%)	0.834	0.198
Down 15-20% (mean –16.8%)	0.625	0.103
Down 20-25% (mean –20.7%)	0.480	0.554
Down >25% (mean –41.2%)	0.542	0.565

The possibility of accident migration has been mentioned in the case of traffic calming. It has been suggested that drivers who are delayed by having to slow down through a small town, will try to catch up by speeding up once they have passed the town. Unfortunately, none of the studies that have been reviewed have tried to evaluate whether there is such an effect. It therefore remains a conjecture only.

Treatment: Install speed humps

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Not applicable.

Urban and suburban residential two-lane roads

Speed humps are most commonly used in residential access roads, in a suburban environment. Some of these roads have just a single lane, but most of them are narrow two lane roads, where two cars can pass each other, but not two trucks.

The Institute of Traffic Engineers explains that speed humps are effective in part because they are self-enforcing and create a visual impression that a roadway is not intended for speeding or for through traffic (*83*). Some of the drawbacks of speed humps and speed tables are: the expense of construction and maintenance; potential negative impacts on emergency and service vehicles; increased vehicular noise; inconvenient access; and unsightliness. The ITE also stresses the importance of using signs and/or pavement markings to warn motorists of speed humps in the roadway ahead. Furthermore, speed humps can adversely affect drainage and snow removal.

A total of ten studies that have evaluated the effects of humps have been retrieved. These studies contain a total of 62 estimates of effect. None of the studies have employed state-of-the-art methodology to control for regression-to-the-mean or long-term trends. Some of the studies do, however, provide data on changes in traffic volume associated with the use of humps. Moreover, three studies (Baguley 1982, Webster 1993, Webster and Mackie 1996) have investigated the possibility of accident migration, by studying whether traffic and accidents has increased in roads surrounding those in which humps have been installed. Despite the somewhat disappointing quality of the studies, they have been included as more rigorous studies have not been found.

Forty-nine of the 62 estimates of effect of humps have been rated as low quality and 13 as medium low quality. Thus, a high quality quantification of safety is not available for this measure.

The safety effects of humps stated in Exhibit 3-109 refer to all injury accidents, including single vehicle accidents. There are no estimates of the effect of humps for property-damage-only accidents. It cannot be ruled out that the summary estimates presented in Exhibit 3-109 are confounded by uncontrolled regression-to-the-mean and uncontrolled long-term trends in accident occurrence. Standard errors have been adjusted by a factor of 3 for each low quality estimate of effect and a factor of 2.2 for each medium low quality estimate of effect.

Exhibit 3-109: Effects on injury accidents of speed humps (8)

Author, date	Treatment/ Element	Setting	Road type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Adjacent to roads with speed humps	Urban/ Suburban	Residential Two-lane, Volume not reported	All types Injury	0.950	0.059
Elvik and Vaa, 2004	Install speed humps	Urban/ Suburban	Residential Two-lane, Volume not reported	All types Injury [1]	0.496	0.130
Elvik and Vaa, 2004	Install speed humps	Urban/ Suburban	Residential Two-lane, Volume not reported	All types Injury [2]	0.600	0.163

Notes: 1) All studies (62 estimates);
2) Adjusted for changes in traffic volume (41 estimates)

Humps have been found to deter traffic. If the summary estimate of effect is adjusted for this, showing the effect of humps on accidents if traffic volume remains unchanged, there is a reduction of injury accidents of 40 percent. Since humps deter traffic, there has been a concern that traffic migrates to alternative routes, leading to an increase of accidents on these routes. This does not appear to be the case, as the number of accidents has been found to go down slightly even on roads surrounding those where humps have been installed. The studies did not control for regression-to-the-mean. The estimates given in Exhibit 3-109 may therefore overstate the true effect of humps. In studies stating speed, mean speed was reduced from an average of 47.7 km/h before humps were installed to 36.3 km/h after humps were installed (29.6 miles/h to 22.6 miles/h). This suggests that the observed accident reduction was not entirely attributable to regression-to-mean.

Treatment: Install raised pedestrian crosswalks

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Not applicable.

Urban and suburban residential two-lane roads

Raised pedestrian crossings tend to be applied most often on business streets, in an urban environment. These streets would usually be two-lane roadways. Raised pedestrian crossings are applied both at intersections and midblock. The results presented include both cases, as most studies do not state whether the crossings were at intersections or midblock.

Four studies have been found, that have evaluated the safety effects of raised pedestrian crossings. These studies contain a total of ten estimates of effect. None of the studies have controlled for regression-to-the-mean or long-term trends in accident occurrence. For raised pedestrian crosswalks, 8 estimates have been rated as low quality and 2 as medium low quality. Thus, a high quality quantification of safety is not available for this measure.

The safety effects of raised pedestrian crosswalks in Exhibit 3-110 refer to pedestrian accidents or accidents involving motor vehicles only. The latter category includes all accidents that involve one or more motor vehicles, but not a pedestrian. It cannot be ruled out that the summary estimates presented in Exhibit 3-110 are confounded by uncontrolled regression-to-the-mean and uncontrolled long-term trends in accident occurrence. Standard errors have been adjusted by a factor of 3 for each low quality estimate of effect and a factor of 2.2 for each medium low quality estimate of effect.

Exhibit 3-110: Effects on injury accidents of raised pedestrian crosswalks (8)

Author, date	Treatment/ Element	Setting	Road type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	All accidents, Injury	0.642	0.543
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	Pedestrian accidents, Injury	0.545	0.937
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	Vehicle accidents, Injury	0.697	0.667

Raised pedestrian crossings appear to reduce both pedestrian accidents and vehicle accidents. There are few studies and these have not controlled adequately for potentially confounding factors. The adjusted standard errors are of the same magnitude as the summary estimate of effect, indicating that there is very large uncertainty in these estimates. Despite this, it is not implausible to believe that raised pedestrian crossings do reduce accidents, since they reduce speed.

Treatment: Install transverse rumble strips as a traffic calming device

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials; Freeways; Expressways

Not applicable.

Urban and suburban residential two-lane roads

Transverse rumble strips have, in most of the evaluation studies reviewed and included here, been applied on the approaches to intersections. This measure is also included in the section dealing with traffic calming in intersections.

Eleven studies have been identified that have evaluated transverse rumble strips. These studies contain a total of 65 estimates of effect. Nearly all the studies are simple before-after studies. None of these studies have controlled for regression-to-the-mean or long-term trends in safety. One study employed a matched comparison group. However, this study did not explicitly control for any confounding factors, and the accident samples that were matched were both very small.

Of the 65 estimates of effect of transverse rumble strips, 59 have been rated as low quality, 2 as medium low quality, and 4 as medium high quality. Thus, a high quality quantification of safety is not available for this measure.

The safety effects of transverse rumble strips in Exhibit 3-111 refer to all accidents. This is likely to include both accidents on the approaches to intersections and accidents in the intersections. It cannot be ruled out that the summary estimates presented in Exhibit 3-111 are confounded by uncontrolled regression-to-the-mean and uncontrolled long-term trends in accident occurrence. Standard errors have been adjusted by a factor of 3 for each low quality estimate of effect, a factor of 2.2 for each medium-low quality estimate of effect, and factor of 1.8 for each medium-high quality estimate of effect.

Exhibit 3-111: Effects on accidents of transverse rumble strips (8)

Author, date	**Treatment/ Element**	**Setting**	**Road type & Volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa, 2004	Install transverse rumble strips	Urban and suburban	Residential two-lane roads, volume not reported	All accidents, all severities	0.663	0.105
Elvik and Vaa, 2004	Install transverse rumble strips	Urban and suburban	Residential two-lane roads, volume not reported	All accidents, Injury	0.643	0.118
Elvik and Vaa, 2004	Install transverse rumble strips	Urban and suburban	Residential two-lane roads, volume not reported	All accidents, PDO	0.725	0.414

Transverse rumble strips in traffic calming appear to reduce accidents by about 30 percent. Again, studies do not control adequately for potentially confounding factors. None of the studies listed in Table 4 have controlled for regression-to-the-mean or long-term trends. A few studies have evaluated effects on speed, as well as effects on accidents. On the average, these studies find that mean speed has been reduced from 40 mph to 35.3 mph (64.3 km/h to 56.8 km/h), which lends some plausibility to the observed accident reduction.

3.2.7. Speed Zoning

Speed zoning refers to the practice of applying a speed limit to a section of highway that is different from the speed limit applying to adjacent roadway segments. One would, as an example, typically lower the speed limit on a main highway passing through small town. The highway would, for example, have a speed limit of 80 km/h (50 mph) outside the town, reduced to 50 km/h (31 mph) for, say, 2 kilometres through the town. This type of speed zoning is very widely applied in nearly all motorized countries. In this section, the expected effects on safety of speed zoning will be summarised.

For future editions of the HSM, the safety effects of targeted and automated speed enforcement at these corridors could be found in this section.

This section discusses the effect of speed zoning on accidents. These effects have been evaluated in many studies. Relevant studies have been reviewed by Elvik et al. (2004). The results of this review will be used in this section.

Exhibit 3-112: Resources examined to investigate the safety effect of speed zoning on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(*84*) (Elvik, R., Christensen, P., and Amundsen, A., "Speed and Road Accidents An Evaluation of the Power Model." Oslo, Norway, Transportokonomisk Institutt, (2004))	A meta-analysis of a large number of studies that have evaluated the effects of changes in speeds on the number and severity of accidents	Added to synthesis.
(Stuster, J., Coffman, Z., and Warren, D., "Synthesis of Safety Research Related to Speed and Speed Management." FHWA-RD-98-154, McLean, Va., Federal Highway Administration, (1998))	A synthesis of research findings on the safety effects of measures including speed limits used to manage speed	Suggested by 17-18(4). Duplicates many of the studies reviewed in Elvik et al. (2004) meta-analysis. Not added to synthesis.
(Transportation Research Board, "Special Report 254: Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits." Washington, D.C., Transportation Research Board, National Research Council, (1998))	Reviews studies that provide information o the effectiveness of speed zoning	Suggested by 17-18(4). Reviewed. Relevant studies included in Elvik et al. (2004) meta-analysis. Not added to synthesis.
(Agent, K. R., Pigman, J. G., and Weber, J. M., "Evaluation of Speed Limits in Kentucky." Lexington, Kentucky Transportation Center, University of Kentucky, (1997))	Evaluated the effect on crash rates of 100 speed zones in KY by comparing the speed zones to adjacent sections where the speed limit was not lowered.	Suggested by 17-18(4). Reviewed. Too few data to be included in meta-analysis
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	Citation from the Ministry of Transportation of British Columbia library e-catalogue	Suggested by 17-18(4). No AMFs. Not added to synthesis.
(Taylor, W. C. and Coleman, F., "Analysis of Speed Zoning Effectiveness." FHWA-MI-RD-88-01, Washington, D.C., Federal Highway Administration, (1988))	Conducted a before/after w/control study on the effect on crashes in twenty speed zones.	Suggested by 17-18(4). Too few data to be included in meta-analysis
(Kadell, D. J., "Traffic Safety Impact of Driver Improvement Countermeasures Targeting 55-MPH Speed Limit Compliance." Sacramento, Calif., California State Department of Motor Vehicles, (1984))	Citation from the Ministry of Transportation of British Columbia library e-catalogue	Suggested by 17-18(4). Enforcement measures, no AMFs. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Cleveland, D. E., "Speed and Speed Control." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 6, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	This is the sixth in a series of publications and provides research findings on the safety effects of specific design and control features	Too few details to be included in meta-analysis.

The review reported by Elvik, Christensen and Amundsen (2004) summarises the findings of 97 studies that have evaluated the relationship between changes in speed and changes in the number of accidents or the severity of injuries (*84*). The results of this review will be presented here. Evidence is based on the best studies. This study is considered to be of high quality; therefore the standard error has been adjusted by a factor of 1.2.

Exhibit 3-113 shows the expected effects of changes in speed on the number of accidents. Changes in speed are stated as the percentage change in the mean speed of traffic. Changes in accidents are stated as odds ratios. Uncertainty is stated as the adjusted standard error.

The range of changes in speed included in Exhibit 3-113 goes from a 5% increase to a 15% reduction. It has been assumed that the normal application of speed zoning would be as a measure designed to reduce speed. In most cases, however, the change in mean speed resulting from the introduction of a new speed limit is smaller than 15%. A 15% reduction corresponds, for example, to a reduction of mean speed from 60 km/h to 51 km/h (37 to 32 mph).

The results presented in Exhibit 3-113 are all based on the so-called Power Model of the relationship between changes in speed and changes in road safety (*85*). According to this model, the relative change in the number of accidents is a power function of the relative change in the mean speed of traffic. The study reported by Elvik et al. (2004) was designed to evaluate the Power Model, and relied on a much larger set of studies than those used by Nilsson (*85*) to develop the model.

The results listed in Exhibit 3-113 include all types of traffic environments and all types of highways. Meta-regression models applied to the data indicate that the relationship between changes in speed and changes in accidents is constant and does not depend on local characteristics of highways or the traffic environment. Indeed, one can reasonably interpret the Power Model as a statement of universal laws of physics, applicable everywhere, but of course never observed in ideal form in real data.

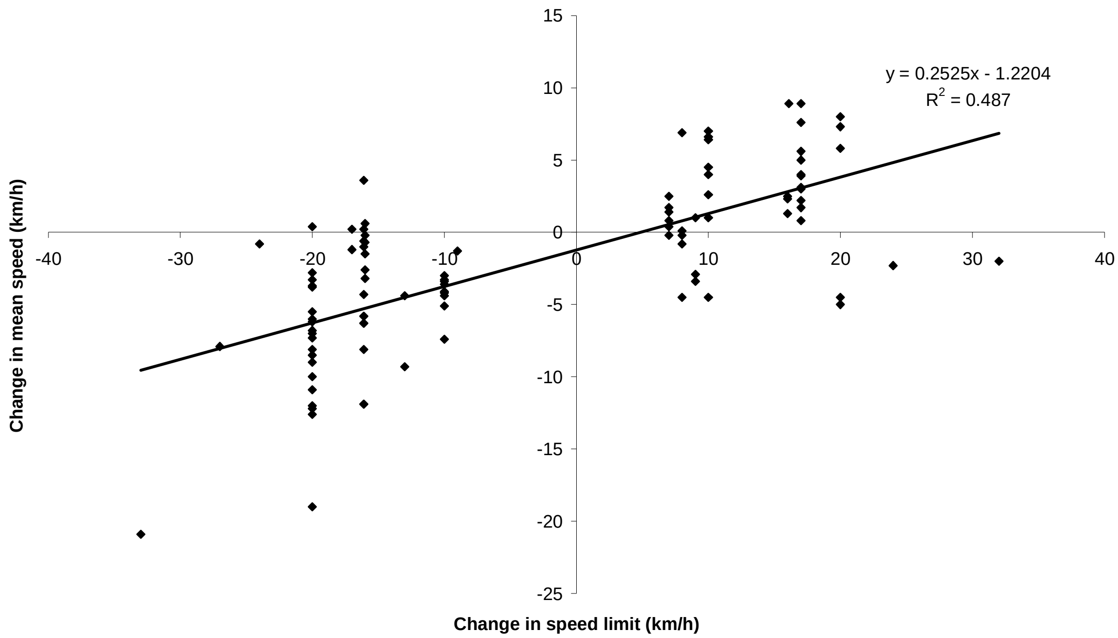
Exhibit 3-113: Effects on accidents of changes in the mean speed of traffic (84)

Change in mean speed	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
5% down	All types, Fatal	0.831	0.045
	All types, Injury	0.926	0.026
	All types, PDO	0.950	0.038
10% down	All types, Fatal	0.684	0.093
	All types, Injury	0.854	0.054
	All types, PDO	0.900	0.077
15% down	All types, Fatal	0.557	0.143
	All types, Injury	0.784	0.084
	All types, PDO	0.850	0.119
5% up	All types, Fatal	1.192	0.043
	All types, Injury	1.076	0.025
	All types, PDO	1.050	0.036

The Power Model has been found to describe the relationship between changes in speed and changes in road safety quite well. The next question that must be answered is “What is the likely effect of changes in speed limit on the mean speed of traffic?” Exhibit 3-114 is intended to shed light on this question.

Change in speed limit is plotted horizontally; change in mean speed is plotted vertically. It is seen that there is a positive relationship between changes in speed limits and changes in mean speed, but the data are fairly widely scattered around the fitted line. On the average, the change in the mean speed of traffic is close to 25% of the change in speed limit. This means that if the speed limit is reduced by 6 mph (10 km/h), mean speed is likely to change by about 1.6 mph (2.5 km/h). This is a rule of thumb only, but it reflects the fact that there is rarely a fully proportional change in mean speed if the speed limit is changed.

Exhibit 3-114: Relationship between changes in speed limits (km/h) and change in the mean speed of traffic (km/h). Based on studies reviewed by Elvik et al. (84)



3.2.8. On-Street Parking

Parking facilities are defined as terminals that are used for temporary vehicle storage. There are two general types of parking facilities: at the curb or on-street parking, and in off-street lots or structures (*86*). Parking safety is influenced by an extremely complex set of driver and pedestrian attitudinal and behavioral patterns (*53*). According to Box, certain kinds of accidents are typically caused by curb-parking operations: sideswipe and rear-end crashes resulting from lane changes due to the physical presence of the parking vehicle or contact with the parked car; sideswipe and rear-end crashes resulting from vehicles stopping prior to entering the curb space; sideswipe and rear-end crashes resulting from vehicles exiting parking stalls and making lane changes; crashes resulting from passengers alighting from parked vehicles street-side doors; crashes with vehicles pulling out of side streets/driveways and pedestrians obscured by parked vehicles (*87*).

The conventional wisdom in traffic engineering has always been that angle parking results in high accident rates (*88*). Box adds that many traffic engineers are opposed to the use of angle parking due to safety concerns and have worked towards its removal or replacement with parallel parking (*87*). Despite this concern, some cities have implemented angle parking to provide additional parking spaces on streets that are sufficiently wide enough in order to meet parking demands (*89*).

This section will provide information on the safety effect of on-street parking on roadway segments. The effect on the safety of motorists, pedestrians, and bicyclists will be addressed. Crashes on roadway segments with on-street parking will be compared to crashes on similar roadway segments without on-street parking. On-street parking configuration (angle, parallel) and parking on one side versus both sides will also be addressed. Some of the issues to consider here include: adjacent land use (schools, commercial, type of pedestrians, traffic mix) loading zones; time of day, length of time parking, parking frequency and turnover rate, and bicycle on-street parking.

Exhibit 3-115: Resources examined to investigate the safety effect of on-street parking on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Bonneson, J., Zimmerman, K, and Fitzpatrick, K., "Roadway Safety Design Synthesis." College Station, Texas Transportation Institute, Texas A&M University, (2005))	Conducted a critical review of the literature and an evaluation of reported trends and safety relationshiops.	Added to synthesis for effect of angle versus parallel parking.
(*3*) (Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004))	Study developed a statistical model to estimate the frequency of non-intersection accidents on urban four-lane undivided roads.	Added to synthesis for On-street Parking. Only used models for off-the-road accidents since they were the only models to include parking as a predictor variable.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis; t and s values were calculated using data from Table 3.15.1 (p. 555).
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Study reviews and brings together the best available evidence on the safety impact of traffic operations. All the studies reviewed report on crash occurrence, severity or proven crash surrogates.	Not added to synthesis. The two studies reviewed by (Main, 1984; McCoy et al., 1990) were already included in the meta-analysis by Elvik and Vaa.
(Nawn, J. A., "Back-in Angle Parking in the Central Business District." Seattle, Wash., 2003 Institute of Transportation Engineers Annual Conference, (2003))	Study examines the operational and capacity issues related to back-in, angle parking.	Not added to synthesis. No information on safety, only capacity and operational issues were considered.
(*87*) (Box, P., "Angle Parking Issues Revisited, 2001." ITE Journal, Vol. 72, No. 3, Washington, D.C., Institute of Transportation Engineers, (2002) pp. 36-47.)	Summarizes data from published and unpublished data on the safety effect of parking; compares findings to 1978 FHWA findings; considers street classification	Added to synthesis. Suggested by NCHRP 17-18(4). Only 1 study cited by Box is before-after evaluation of parking; remaining studies only present accident rates; t and s values calculated using data available from single before-after study.
(Hunter, W. W. and Stewart, J. R., "An Evaluation Of Bike Lanes Adjacent To Motor Vehicle Parking." Chapel Hill, Highway Safety Research Center, University of North Carolina, (1999))	Cross sectional study of two configurations of bicycle lanes in combination with on-street parking	Not added to synthesis. Suggested by NCHRP 17-18(4). Reference focused on bicycle operations and does not provide quantitative evidence of safety effects of parking.

DOCUMENT	DESCRIPTION	COMMENT
(*89*) (McCoy, T. A., McCoy, P. T., Haden, R. J., and Singh, V. A., "Safety Evaluation of Converting On-Street Parking from Parallel to Angle." Transportation Research Record 1327, Washington, D.C., Transportation Research Board, National Research Council, (1991) pp. 36-41.)	Before and after study evaluated the effects of converted on-street parallel parking to angle parking in Lincoln, Nebraska	Added to synthesis. Suggested by NCHRP 17-18(4). Only discussion about previous before-after studies added, actual analysis was not used because this study was part of the meta-analysis by Elvik and Vaa that has already been included in this synthesis.
(Humphreys, J. B., Box, P. C., Sullivan, T. D., and Wheeler, D. J., "Safety Aspects of Curb Parking-Executive Summary." FHWA-RD-79-75, Washington, D.C., Federal Highway Administration, (1978))	FHWA report analyzed the relationship between on-street parking and crashes using data from 10 cities. Focus of study is on capacity and operational issues, not safety.	Suggested by NCHRP 17-18(4). Very limited information on safety.
(*53*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Report is a synthesis of 17 safety research areas, including a review of previous research studies dealing with on-street parking.	Added to synthesis. Crash data from Tables 11, 17, and 19 were used. Data from other tables were not used because they either provided insufficient data to calculate t and s values or were already included in the meta-analysis by Elvik and Vaa (2004).
(Mayer, P. A. and Rankin, W. W., "One-Way Streets and Parking." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 10, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Study discusses parking and accident rates using findings from previous studies. Reference cites one study by Seburn that compared accident rates for different types of parking controls and roadway widths. However, based on the information provided, it is unclear if such comparisons are appropriate, particularly since the study does not mention if any other potential confounding factors are accounted for.	Not added to synthesis. Insufficient data provided to calculate t and s values

Although there have been a number of studies that have examined the issue of accident rates or frequencies associated with different types of parking configurations, the large majority are naïve before-after studies that involve changes from angle to parallel parking (*89*).

While the results from the synthesis of studies as shown below appear to indicate that by and large, the reduction or elimination of on-street parking reduces the number of accidents, there are two major issues for consideration: accident migration; and the appropriateness of the methods used in previous studies.

With regards to the issue of accident migration or spillover, it should be noted that all of the studies only show how the parking restrictions have affected the street or streets where the treatments are introduced. According to Elvik and Vaa, parking may simply be transferred to other streets, and it cannot be ruled out that the number of accidents may actually increase on streets where parking demand increases (*8*). It may be necessary to conduct area-wide studies (including an examination of off-street parking in the vicinity of the treatment sites) to properly assess the safety effects of any changes to parking regulations and policies (*53*).

In terms of the shortcomings of the methodologies adopted in previous research studies, as McCoy et al. point out, many of these before-after studies do not account for the change in accident exposure associate with the change in parking configuration. For example, when angle parking is changed to parallel parking, accident exposure is reduced because there are few parking spaces remaining after the conversion. Therefore, reductions in accidents that have been associated with changes from angle to parallel parking may have been caused by changes in accident exposure rather than by differences in the types of parking maneuvers associated with different parking configurations (*89*).

In fact, by comparing the parking-related accident rates before and after the conversion of 27 downtown blocks from parallel to angle parking, and taking into account the accident exposure (by calculating before and after accident rates in terms of accidents per million space-hours per 1,000 parkers per million vehicle miles), McCoy et al. demonstrated that there was no significant difference in the mean parking-related accident rates (*89*). Results from the study by McCoy et al. have been incorporated into the meta-analysis by Elvik and Vaa. Elvik and Vaa concur by stating that many of the previous studies investigating the safety effects of parking are naïve before-after studies that do not account or control for regression-to-the-mean and in many cases, parking control measures have been combined with other measures so the effect of the parking regulations themselves alone cannot be determined (*8*).

Although the safety effects of these factors have not been quantified in any studies to date, several previous research efforts such as those by Box (1964; 1968), Seburn (1967), and Humphreys et al. (1978) have reported that street width, the surrounding land use (which affect the volume of vehicle, pedestrians and bicyclists), and parking utilization may be significant factors (*53*).

Treatment: Prohibit on-street parking

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials

Hoffman et al. conducted a simple before-after comparison of accident frequencies resulting from the prohibition of parking on a 64-foot wide major arterial (*53*). The results from the study are shown in Exhibit 3-116. The index of effectiveness was adjusted to account the 32% increase in traffic volume to 30,000 veh/day, thus the index of effectiveness was divided by 1.32.The study was assigned a medium-low rating; the values for the indices of effectiveness were calculated using available crash data and a MCF of 2.2 was applied to the s ideal calculated based on the number of before crashes and the ratio of after/before duration.

Elvik and Vaa conducted a meta-analysis of a number of studies related to the prohibition of parking on urban arterials and collectors, and found that this change in parking policy reduces the number of total, injury and PDO accidents (p. 555) (*8*). The authors remarked that although the traffic volumes varied greatly at the different sites examined, this particular treatment tended to be implemented on higher volume arterials that experienced traffic volumes in the 40,000 veh/day range. The results from the meta-analysis are summarized in Exhibit 3-116. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Combining the results of Hoffman et al. with Elvik and Vaa for urban arterials results in AMF values of 0.78 (S=0.05) and 0.72 (S=0.02) for injury accidents and PDO accidents respectively. Note that while both studies quantified the safety impacts of prohibiting on-street parking at the sites examined, neither accounted for the potential effects of accident migration or spillover to adjacent roads with parking (Exhibit 3-116).

Exhibit 3-116: Safety effectiveness of prohibiting on-street parking on urban roadway segments

Author, date	**Treatment / Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Hoffman et al as cited in Various, 1982	Prohibit on-street parking	Urban	Major Arterial (64-ft wide), AADT = 30,000	All types, all severities	0.58	0.08
Hoffman et al as cited in Various, 1982	Prohibit on-street parking	Urban	Major Arterial (64-ft wide), AADT = 30,000	All types, injury	0.65	0.14
Elvik and Vaa, 2004	Prohibit on-street parking	Urban	Mostly Arterial	All types, injury	0.80	0.05
			All types, injury	**Combined**	**0.78**	**0.05**
Hoffman et al as cited in Various, 1982	Prohibit on-street parking	Urban	Major Arterial (64-ft wide), AADT = 30,000	All types, PDO	0.52	0.10
Elvik and Vaa, 2004	Prohibit on-street parking	Urban	Mostly Arterial	All types, PDO	0.73	0.02
			All types, PDO	**Combined**	**0.72**	**0.02**

Using data from Washington State (1993 to 1996), multivariate statistical models were developed by Hauer et al. in order to predict the non-intersection accident frequency of urban four-lane undivided roads. Six separate models were estimated for "off-the-road" and "on-the-road" Property Damage Only (PDO), Injury, and Total accidents. "Off-the-road" accidents were identified using the Impact Location Code in the HSIS database on which the models were derived. Accidents occurring "Off Road Past Shoulder" and "On Shoulder" were classified as off-the-road accidents. The traffic volumes for the sites studied had a range of 2,500 to 68,500 veh/day with the mean being 24,900 veh/day. The models derived for off-the-road accidents are shown in Equation 3-12 through Equation 3-14. Models used to predict on-the-road accidents have been omitted because parking was not used as a predictor variable in those models.

Equation 3-12: Regression model for off-the-road PDO accidents (3).

Off-the-road PDO Accidents:

$$y = \alpha_{year} \left(\begin{array}{l} \text{Segment Length for Prediction x } (X^{0.520} e^{0.003xX}) \text{ x} \\ (1.19 \text{ if ST = Curb or Wall, otherwise } 0.48 + 0.19 \text{ x SWC) x} \\ (1.10 \text{ if PC, } 1.51 \text{ if NPC, } 0.42 \text{ if VS, } 0.81 \text{ if NVS) x} \\ e^{0.041x\text{Degree of Curve}} \text{ x } (1.079 \text{ if parking is prohibited and otherwise } 1) \text{ x} \\ (0.759 \text{ if TWLT and otherwise } 1) \text{ x} \\ (2.087 \text{ if Speed Limit} \leq 30 \text{ mph, } 1.213 \text{ if Speed Limit} \geq 45 \text{ mph and otherwise } 1) \end{array} \right)$$

Equation 3-13: Regression model for off-the-road Injury accidents (3).

Off-the-road Injury Accidents:

$$y = \alpha_{year} \left(\begin{array}{l} \text{Segment Length for Prediction x } (X^{0.815} e^{-0.069xX}) \text{ x} \\ (1.16 \text{ if ST = Curb or Wall, otherwise } 0.76 + 0.83 \text{ x SWC) x} \\ (1.35 \text{ if PC, } 1.03 \text{ if NPC, } 1.31 \text{ if VS, } 0.62 \text{ if NVS) x} \\ e^{0.056x\text{Degree of Curve}} \text{ x } (1.258 \text{ if parking is prohibited and otherwise } 1) \text{ x} \\ (0.832 \text{ if TWLT and otherwise } 1) \text{ x} \\ (1.287 \text{ if Speed Limit} \leq 30 \text{ mph, } 1.374 \text{ if Speed Limit} \geq 45 \text{ mph and otherwise } 1) \end{array} \right)$$

Equation 3-14: Regression model for total off-the-road accidents (3).

Total Off-the-road Accidents:

$$y = \alpha_{year} \left(\begin{array}{l} \text{Segment Length for Prediction x } (X^{0.631} e^{-0.020xX}) \text{ x} \\ (1.03 \text{ if ST = Curb or Wall, otherwise } 0.52 + 0.125 \text{ x SWC) x} \\ (1.20 \text{ if PC, } 1.28 \text{ if NPC, } 0.93 \text{ if VS, } 0.72 \text{ if NVS) x} \\ e^{0.051x\text{Degree of Curve}} \text{ x } (1.153 \text{ if parking is prohibited and otherwise } 1) \text{ x} \\ (0.797 \text{ if TWLT and otherwise } 1) \text{ x} \\ (1.70 \text{ if Speed Limit} \leq 30 \text{ mph, } 1.29 \text{ if Speed Limit} \geq 45 \text{ mph and otherwise } 1) \end{array} \right)$$

Given the multiplicative form of the regression equations, calculation of AMF values by taking the ratio of the number of accidents following the prohibition of parking over the number of accidents when parking is allowed, results in each of the remaining terms canceling out, leaving only the parameter for parking. For example, in the calculation of the AMF for off-the-road PDO accidents, the ratio $y_{\text{parking prohibited}}/y_{\text{parking allowed}}$ results in all terms canceling out except for the parameter for parking (which in this case is 1.079). This means that prohibiting parking will result in an AMF value of 1.079 for off-the-road accidents. Based on the results from the study by Hauer et al., it appears that prohibiting parking on urban four-lane undivided roads increased the number of off-the-road accidents. There were insufficient data to calculate standard error values for these AMF values. The results from the study are summarized in Exhibit 3-117.

Exhibit 3-117: Safety effectiveness of prohibiting on-street parking on urban roadway segments to off-the-road areas

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hauer et al., 2004	Prohibit on-street parking	Urban	Four-lane undivided roads, AADT 2,500-68,500	Off-the-road PDO Accidents	1.079	n/a
Hauer et al., 2004	Prohibit on-street parking	Urban	Four-lane undivided roads, AADT 2,500-68,500	Off-the-road Injury Accidents	1.258	n/a
Hauer et al., 2004	Prohibit on-street parking	Urban	Four-lane undivided roads, AADT 2,500-68,500	Off-the-road all severities	1.153	n/a

Treatment: Prohibit on-street parking on one side of the road

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials

Elvik and Vaa meta-analyzed a number of studies that investigated the safety effects of prohibiting parking on one-side of urban arterials and collectors (p. 555) (*8*). The traffic volumes at the sites examined were not reported. The results from the meta-analysis are summarized in Exhibit 3-118. As shown, Elvik and Vaa found that this particular treatment appeared to increase the number of injury accidents and resulted in an AMF value of 1.49 (S=0.78) for injury accidents. Elvik and Vaa added that the explanation for this increase is not known. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-118: Safety effectiveness of prohibit on-street parking on one side of urban roadway segments

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Prohibit parking on one side of road	Urban	Arterials and Collectors, volume not reported	All types, Injury	1.49	0.78

Treatment: Convert free to regulated on-street parking

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials

Elvik and Vaa carried out a meta-analysis of a number of studies that examined the safety effects of regulating previously unrestricted parking (such as time limited parking, reserved parking, area/place limited parking, or implementing parking charges) on urban arterials and collectors (p. 555) (*8*). The traffic volumes at the sites examined were not reported. The results from the meta-analysis are summarized in Exhibit 3-119. As shown, Elvik and Vaa found that this particular treatment appears to slightly reduce injury accidents but increase property damage only accidents, resulting in AMF values of 0.94 (S=0.08) and 1.19 (S=0.05) for injury accidents and PDO accidents, respectively. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-119: Safety effectiveness of converting free to regulated on-street parkings (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Convert free to regulated parking	Urban	Mostly Arterial, volume not reported	All types, Injury	0.94	0.08
Elvik and Vaa, 2004	Convert free to regulated parking	Urban	Mostly Arterial, volume not reported	All types, PDO	1.19	0.05

Treatment: Implement time-limited on-street parking restrictions

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials and collectors

Through a meta-analysis of a number of studies, Elvik and Vaa examined the safety effects of implementing time-limited parking restrictions to regulate previously unrestricted parking on urban arterials and collectors (p. 555) (*8*). The traffic volumes at the sites examined were not reported. The results from the meta-analysis are summarized in Exhibit 3-120. Elvik and Vaa found that this particular treatment appears to reduce the number of accidents, particularly parking-related accidents, resulting in AMF values of 0.89 (S=0.06) and 0.21 (S=0.09) for total accidents and parking-related accidents, respectively. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-120: Safety effectiveness of implementing time-limited on-street parking (8)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Implementing time-limited parking restrictions	Urban	Mostly Arterial, volume not reported	All types, all severities	0.89	0.06
Elvik and Vaa, 2004	Implementing time-limited parking restrictions	Urban	Mostly Arterial, volume not reported	Parking-related Accidents, all severities	0.21	0.09

Treatment: Convert angle parking to parallel parking

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials; Urban two-lane roads

The Utah Department of Transportation (DOT) conducted a simple before-after comparison of accident frequencies resulting from the conversion of angle parking to parallel parking on urban streets with widths ranging from 58 to 108 ft (*53*). Traffic volumes were not reported. The results from the study are summarized in Exhibit 3-121. The study was assigned a medium-low rating; the values for the indices of effectiveness were calculated using available crash data and a method correction factor of 2.2 was applied to the s ideal calculated based on the number of before crashes and the ratio of after/before duration .

Crandall investigated the safety effects of the same treatment through a cross-section study that matched two similar blocks using traffic volume (7,500 veh/day) and width (59 feet) of the rights-of-way (*53*). The results from the study are summarized in Exhibit 3-121. The study was assigned a low rating; the values for the indices of effectiveness were calculated using available crash data and a method correction factor of 5.0 was applied to the s ideal calculated based on the number of before crashes and the exposure ratio.

Elvik and Vaa conducted a meta-analysis of a number of studies that focused on this treatment and these results are summarized in Exhibit 3-121 (p. 555) (*8*). The sites examined were mostly local residential streets. The traffic volumes at the sites examined were not reported. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Combining the results of Crandall and the Utah DOT with the results from the meta-analysis by Elvik and Vaa for urban arterials results in AMF values of 0.67 (S=0.06), 0.38 (S=0.06) and 0.60 (S=0.26) for total accidents, parking-related accidents and injury/fatal accidents respectively (Exhibit 3-121). None of the three studies addressed the issue of potential accident migration or spillover onto adjacent roadways with on-street parking facilities.

Exhibit 3-121: Safety effectiveness of converting angle parking to parallel parking on urban roadway segments

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Utah DOT as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Not specified	All types, all severities	0.72	0.11
Crandall as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Major Arterial (58-ft wide), AADT = 7,500	All types, all severities	0.47	0.47
Elvik and Vaa, 2004	Transition from angle (diagonal) to parallel parking	Urban	Mostly local (residential) streets, volume not reported	All types, all severities	0.65	0.07
			All types, all severities	**Combined**	**0.67**	**0.06**
Utah DOT as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Not specified	Parking-related Accidents, all severities	0.43	0.18
Crandall as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Major Arterial (58-ft wide), AADT = 7,500	Parking-related Accidents, all severities	0.35	0.46
Elvik and Vaa, 2004	Transition from angle (diagonal) to parallel parking	Urban	Mostly local (residential) streets, volume not reported	Parking-related Accidents, all severities	0.37	0.07
			Parking-related Accidents, all severities	**Combined**	**0.38**	**0.06**
Utah DOT as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Not specified	All types, Injury and fatal Accidents	0.59	0.27
Crandall as cited in Various, 1982	Transition from angle (diagonal) to parallel parking	Urban	Major Arterial (58-ft wide), AADT = 7,500	All types, Injury and fatal Accidents	0.80	1.34
			All types, Injury and fatal Accidents	**Combined**	**0.60**	**0.26**

Bonneson (2005) developed an AMF for on-street parking based upon previous work by Box *(87)* and McCoy et al. (*171*) (*172*). The AMF for on-street parking includes the crash effects for angle vs. parallel parking, the type of development along the street, and the proportion of curb length with on-street parking. The AMF for on-street parking as formulated by Bonneson et al. is as follows:

$$AMF_{pk} = 1 + p_{pk} (f_{pk} - 1)$$

$$f_{pk} = (1.10 + 0.365 I_{cs} + 0.609 p_{b/o}) [(f_{ap/pp} - 1.0) p_{ap} + 1.0]$$

where:

AMF_{pk}	=	accident modification factor for on-street parking
p_{pk}	=	proportion of curb length with on-street parking (= 0.5 L_{pk}/L)
L_{pk}	=	curb length with on-street parking (mi)
L	=	roadway segment length (mi)
I_{cs}	=	indicator variable for cross-section (= 1 for two-lane street; 0 otherwise)
$p_{b/o}$	=	for that part of the street with parking, the proportion that has business or office as adjacent land use
$f_{ap/pp}$	=	ratio of crashes on streets with angle parking to crashes on streets with parallel parking (assume a value of 2.34)
p_{ap}	=	for that part of the street with parking, the proportion with angle parking

The base condition for this AMF is "no parking." Bonneson derived the value of 2.34 for $f_{ap/pp}$ based upon data from Box *(87)* and McCoy et al. (*171*).

Treatment: Convert parallel parking to angle parking

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials

Box reviewed a number of previous research studies, including a simple before-after comparison by Brazelton that investigated the safety effects of converting parallel parking to angle parking on streets in the central business district (*87*). Traffic volumes were not reported. The results from the study are summarized in Exhibit 3-122. The study was assigned a low rating (simple before-after study with 1.5 year before and after period); the values for the indices of effectiveness were calculated using available crash data and a method correction factor of 3.0 was applied to the s ideal calculated based on the number of before crashes and the ratio of after/before duration. The AMF and standard error values are noticeably large due to the small sample size in crash data used, as well as the large method correction factor applied.

Exhibit 3-122: Safety effectiveness of converting parallel parking to angle parking on urban roadway segments

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Brazelton as cited in Box, 2001	Transition from parallel parking to angle (diagonal) parking	Urban	Major streets in the Central Business District, volume not reported	All types, all severities	2.11	2.56
Brazelton as cited in Box, 2001	Transition from parallel parking to angle (diagonal) parking	Urban	Major streets in the Central Business District, volume not reported	Parking-related Accidents, all severities	1.18	0.73

Treatment: Place pavement markings to delineate parking stalls

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways

Not applicable.

Urban and suburban arterials, collectors, and local streets

Elvik and Vaa carried out a meta-analysis of a number of studies that examined the safety effects of marking parking spaces on urban arterials, collectors and local streets (p. 555) (*8*). The large majority of the sites used in the study comprised of local residential streets with lower traffic volumes. However, the traffic volume range was not reported. The results from the meta-analysis are summarized in Exhibit 3-123. As shown, Elvik and Vaa found that this particular treatment appears to significantly increase total accidents and parking-related accidents, resulting in AMF values of 1.51 (S=0.20) and 2.28 (S=0.53) for total accidents and parking-related accidents, respectively. Elvik and Vaa stated that the reason behind this increase is not known. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 3-123: Safety effectiveness of marking parking spaces on urban roadway segments

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Marking parking places	Urban	Mostly local (residential) streets, volume not reported	All types, all severities	1.51	0.20
Elvik and Vaa, 2004	Marking parking places	Urban	Mostly local (residential) streets, volume not reported	Parking-related Accidents, all severities	2.28	0.53

3.2.9. Intelligent Transportation Systems and Traffic Management Systems [Future Edition]

In future editions of the HSM, this section may provide information on the safety effects of intelligent transportation systems and traffic management systems. This may include traffic management systems, automated speed enforcement, incident management systems, and traffic signal progression. Related roadway network information is provided in Chapter 7. This section may also build on information provided in Chapter 4 for intersection ITS treatments. Potential resources are listed in Exhibit 3-124

Exhibit 3-124: Potential resources on the relationship between intelligent transportation systems and safety

DOCUMENT
(Minnesota DOT Traffic Management Center, "Minnesota Department of Transportation Freeway Traffic Management Program." MDOT, (2003))
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))
(Kyte, M., Shannon, P., and Kitchener, F., "Idaho Storm Warning System Operational Test." ITD No. IVH9316 (601), Boise, Idaho Transportation Department, (2000))
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))
(Jernigan, J. D., "Expected Safety Benefits of Implementing Intelligent Transportation Systems in Virginia: A Synthesis of the Literature." FHWA/VTRC 99-R2, Richmond, Virginia Department of Transportation, (1998))
(Sinha, K. C., Peeta, S., Sultan, M. A., Poonuru, K., and Richards, N., "Evaluation of the Impacts of ITS Technologies on The Borman Expressway Network." FHWA/IN/JTRP-98/5, West Lafayette, Indiana Department of Transportation, (1998))
Annino, "The Effects of ITS Technologies on Accident Rates" 1998
Zein, et al. [Title unknown] 1997
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))
Henk, "San Antonio's Transguide: Analysis of the Benefits" 1997
Persaud et al., "Safety Evaluation of Freeway Traffic Management System in Toronto, Canada" 1996

3.3. Pedestrian and Bicyclist Safety on Roadway Segments

Pedestrians and bicyclists are more vulnerable road users, and consideration of their needs on roadway segments may impact the overall safety performance of a roadway. Several sources are available for information on pedestrian and bicyclist accommodation, such as:

- www.walkinginfo.org
- www.bicycleinfo.org
- AASHTO "Guide for the Planning, Design and Operations of Pedestrian Facilities", 2004 (91)
- "ADA and ABA Accessibility Guidelines for Buildings and Facilities", 2004 (92)

- "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians" by Zegeer et al., 2004 (93)
- "Pedestrian Facilities Users Guide – Providing Safety and Mobility" by Zegeer et al., 2002 (94)
- Parts I and II of "Designing Sidewalks and Trails for Access" by Axelson, Kirschbaum, et al., 1999 and 2001 (95,96)
- "Design and Safety of Pedestrian Facilities: A Recommended Practice of the ITE", 1998 (97)
- "The Effects of Bicycle Accommodations on Bicycle/Motor Vehicle Safety and Traffic Operations" by Wilkinson et al., 1994 (98)
- "Americans with Disabilities Act (ADA) of 1990" (99)

One of the most comprehensive guides to date to describe a wide range of treatments to enhance pedestrian safety and mobility is the PEDSAFE Guide, sponsored by the Federal Highway Administration (*100*). This report provides details of 47 different types of engineering and roadway treatments, in addition to enforcement and educational measures. It also includes a description of 71 "case studies" (or success stories) of various pedestrian treatments which have been implemented in communities throughout the U.S.

The PEDSAFE Guide includes expert system software, which is available at http://safety.fhwa.dot.gov/pedsafe and also at www.walkinginfo.org/pedsafe. This software is a diagnostic tool which allows a user to select treatments based on the types of crash or operating problems at a site, as well as site characteristics (e.g., number of lanes, type of roadway, traffic volume, area type, traffic control devices, intersection or midblock, presence and type of median, speed limit). The system provides information to help identify safety and operational needs. The PEDSAFE Guide and software are intended primarily for engineers, planners, safety officials, but may also be useful to citizens in determining needed pedestrian improvements on streets and highways.

The following sections discussed pedestrian and bicyclist elements on roadway segments, such as sidewalks or shoulders, mid-block crossing design, refuge islands/medians, and bicycle routes.

Future editions of the HSM may include sections on pedestrians and bicyclists in school routes and school zones, and the impact of weather issues on pedestrians and bicyclists on roadway segments.

3.3.1. Sidewalks and Shoulders

According to the Uniform Vehicle Code (1992), a sidewalk is defined as (*101*):

"that portion of a street between the curblines, or the lateral lines of a roadway, and the adjacent property lines, intended for use by pedestrians."

NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians describes sidewalks and walkways, as follows (*93*):

"Sidewalks and walkways provide people with space to travel within the public right-of-way that is separated from roadway vehicles. They also provide places for children to walk, run, skate, ride bikes, and play away from the street. Such facilities also improve mobility for pedestrians and provide access for all types of pedestrian travel to and from home, work, parks, schools, shopping areas, transit stops, etc. Walkways should be part of every new and renovated

roadway, and every effort should be made to retrofit streets that currently do not have sidewalks or walkways."

Providing sidewalks and walkways should incorporate proper facility design with respect to sidewalk or walkway width, separation between the walkway and the roadway (i.e., the "buffer zone"), the type of walking surface, sidewalk slope and grade, the proper placement of poles, posts, news racks, trees, and other street furniture, and other considerations, as discussed in the 2002 "Pedestrian Facilities User Guide - Providing Safety and Mobility" (*94*). In addition, guidelines for providing accessible sidewalks and trails for all pedestrians, including people with disabilities, are provided by the U.S. Access Board in "Designing Sidewalks and Trails for Access, Parts 1 and 2" (*95*,*96*). Good design practices are covered in these guidelines, including such issues as sidewalk design features (grades, slopes, surfaces, lighting), driveway crossings, pedestrian information, curb ramp design, pedestrian crossings, traffic calming measures, and trail planning and design, among other things.

For future editions of the HSM, there is a need to quantify the safety effect of the following elements:

- Sidewalk or walkway width
- Separation between the walkway and the roadway (i.e., the "buffer zone")
- Type of walking surface
- Sidewalk slope and grade, curb ramp design
- Placement of poles, posts, news racks, trees, and other street furniture
- Sidewalk lighting and midblock crosswalk illumination
- Driveway crossings
- Pedestrian and bicyclist information
- Trail planning and design

Exhibit 3-125: Resources examined to investigate the relationship between the provision of sidewalks or shoulders and safety

DOCUMENT	DESCRIPTION	COMMENT
(Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians including the effect on pedestrian safety of sidewalks	Suggested by NCHRP 17-18(4). No additional quantitative information. Not added to synthesis.
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies aimed at reducing pedestrian crashes.	Description of sidewalk added. No additional quantitative information. Not added to synthesis.
(Zegeer, C. V., Seiderman, C., Lagerwey, P., Cynecki, M. J., Ronkin, M., and Schneider, R., "Pedestrian Facilities Users Guide - Providing Safety and Mobility." FHWA-RD-01-102, McLean, Va., Federal Highway Administration, (2002))	Detailed discussion of pedestrian needs and facilities.	No new research results. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*102*) (McMahon, P. J., Zegeer, C. V., Duncan, C., Knoblauch, R. L., Stewart, J. R., and Khattak, A. J., "An Analysis of Factors Contributing to "Walking Along Roadway" Crashes: Research Study and Guidelines for Sidewalks and Walkways." FHWA-RD-01-101, McLean, Va., Federal Highway Administration, (2002))	Analyzed crash data at 47 crash sites and 94 comparison sites; identified the relationship between the provision of sidewalks and 'walking along roadway' crashes	Suggested by NCHRP 17-18(4). Added to synthesis.
(Kirschbaum, J. B., Axelson, P. W., Longmuir, P. E., Mispagel, K. M., Stein, J. A., and Yamada, D. A., "Designing Sidewalks and Trails for Access Part II of II: Best Practices Design Guide." Washington, D.C., Federal Highway Administration, (2001))	Guidelines for providing accessible sidewalks and trails for all pedestrians, including people with disabilities	Not added to synthesis.
(Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))	Summary of safety research study results from Australia.	No new research results. Not added to synthesis.
(Axelson, P. W., Chesney, D. A., Galvan, D. V., Kirschbaum, J. B., Longmuir, P. E., Lyons, C., and Wong, K. M., "Designing Sidewalks and Trails for Access, Part I of II: Review of Existing Guidelines and Practices." Washington, D.C., Federal Highway Administration, (1999))	Guidelines for providing accessible sidewalks and trails for all pedestrians, including people with disabilities	Not added to synthesis.
(*103*) (Hunter, W. W., Stutts, J. S., Pein, W. E., and Cox, C. L., "Pedestrian and Bicycle Crash Types of the Early 1990's." FHWA-RD-95-163, McLean, Va., Federal Highway Administration, (1995))	Contains summary information based on a critical review of safety research on bicycle and pedestrian facilities.	No new research results. Crash statistics added to synthesis.
(Knoblauch, R. L., Tustin, B. H., Smith, S. A., and Pietrucha, M. T., "Investigation of Exposure Based Pedestrian Accident Areas: Crosswalks, Sidewalks, Local Streets and Major Arterials." FHWA/RD/88/038, Washington, D.C., Federal Highway Administration, (1988))	Analyzed pedestrian crashes and exposure under various roadway situations, identified a relationship between pedestrian crashes and the provision of sidewalks by functional class	Suggested by NCHRP 17-18(4). No new research results. Not added to synthesis.
(*104*) (Knoblauch, R. L., Tustin, B. H., Smith, S. A., and Pietrucha, M. T., "Investigation of Exposure Based Pedestrian Accident Areas: Crosswalks, Sidewalks, Local Streets and Major Arterials." FHWA/RD/88/038, Washington, D.C., Federal Highway Administration, (1988))	Compared hazard scores for groups of sites with sidewalks on both sides of the road vs. sites with no sidewalks.	Added to synthesis.
(*105*) (Tobey, H. N., Shunamen, E. M., and Knoblauch, R. L., "Pedestrian Trip Making Characteristics and Exposure Measures." DTFH61-81-00020, Washington, D.C., Federal Highway Administration, (1983))	Study analyzed the safety effects of various traffic and roadway features on pedestrian safety based on exposure and pedestrian crash data.	Added to synthesis.

Treatment: Provide a sidewalk

Very few studies were found that have quantified the effects of sidewalks or walkways on pedestrian crashes or crash risk. This is likely due in part to the fact that pedestrian crashes are relatively rare at any given location and because of the difficulty of finding enough new sidewalk additions to conduct a proper before-after evaluation. Furthermore, installing sidewalks or walkways is more likely to reduce certain types of pedestrian crashes, such as where pedestrians are walking along roadways and are struck by a motor vehicle. In fact, a 1996 study by Hunter, Stutts, Pein, and Cox of pedestrian crash types in six states, found that approximately 7.9 percent (400 of 5,073) of pedestrian crashes involved a pedestrian walking along the roadway (*103*). Since many of these types of pedestrian crashes occur at night and also where no sidewalks or paved shoulders exist, one may expect that providing appropriate sidewalks or shoulders would reduce the probability of such crashes in many situations.

A 2002 study by McMahon, Zegeer, Duncan, Knoblauch, Stewart, and Khattak was conducted to identify the types of risks to pedestrians who are "walking along a roadway" and to quantify the relationship of such crash risks with roadway and neighborhood factors (*102*). The study used a case-control methodology and applied conditional and binary logistic models to determine the effects of various roadway features and socioeconomic and other census data on the likelihood that a site is a pedestrian crash site. A total of 47 crash sites were found, which were matched with 94 comparison sites (i.e., one nearby and one far-away matched comparison site for each crash site) for analysis purposes. Comparison sites were selected which were similar to the crash sites in terms of number of lanes, traffic volume, roadway and shoulder width, vehicle speeds, area type, etc. Nearby comparison sites were selected within the same neighborhood and/or within approximately one mile of the crash site. Far-away sites were matched sites that were selected in neighborhoods or areas on the other side of the county (*102*).

Physical roadway features found to be associated with a significantly higher likelihood of having a "walking along roadway" pedestrian crash included lack of a walkable area, and the absence of sidewalk augmented by higher traffic volume and higher speed limits. Using "risk ratio" and controlling for other roadway factors, the likelihood of a site with a sidewalk or wide shoulder (of 4 feet or wider) having a "walking along roadway" pedestrian crash was 88.2 percent lower than a site without a sidewalk or wide shoulder at the sites studied (*102*). Increased pedestrian crash risk existed for higher speed limits and for higher traffic volumes, as shown in Exhibit 3-126. The authors state that these results "should not be interpreted to mean that installing sidewalks would necessarily reduce the likelihood of pedestrian/motor vehicle crashes by 88.2 percent in all situations. However, the presence of a sidewalk clearly has a strong beneficial effect of reducing the risk of a "walking along roadway" pedestrian/motor vehicle crash" (*102*). Therefore, AMFs were not developed from the results.

When the authors controlled for roadway features, socio-economic factors found to be associated with significantly higher risk of such pedestrian crashes include: high levels of unemployment, older housing units, lower proportions of families within households, and more single-parent households. The authors concluded that such results may suggest that some neighborhoods, due to increased pedestrian exposure or certain types of exposure, may be especially appropriate for adding such pedestrian safety measures as sidewalks, wide grassy shoulders, traffic calming measures, and/or other such treatments. The study also developed guidelines and priorities for installing sidewalks and walkways, based on roadway and land use characteristics (*102*).

Exhibit 3-126: Model results for three variables (Table 4 of (102))

Variable	Coefficient (Estimate)	Standard Error	Chi Square	p-value	Risk Ratio	95% Confidence Intervals
Speed Limit	0.1094	0.0381	8.22	0.0041	1.116	(1.035, 1.202)
Paved Sidewalk	-2.1346	1.077	3.93	0.0474	0.118	(0.014, 0.976)

Traffic Volume	0.0019	0.0010	3.69	0.0549	1.002	(1.000, 1.004)

Note: these results not to be used as AMFs

Discussion: "Hazard scores" with and without sidewalks

A study by Tobey et al. (1983) investigated the relative risks of sidewalks and other traffic and roadway characteristics, using two different measures of pedestrian exposure: pedestrian volume (P), and pedestrian volume multiplied by vehicle volume (P x V). The percent of pedestrian crashes divided by the percent of pedestrian exposure was defined as the "hazard score" for each site, and "hazard scores" were compared for sites with various traffic and roadway characteristics. If the percent of pedestrian crashes was greater than the percent of pedestrian exposure, then the "hazard score" was greater than 1.0, or a pedestrian crash risk greater than average. Where the percent of crashes was less than the percent of exposure, the "hazard score" was computed as the percentage of exposure divided by the percent of crashes and assigned a negative sign (i.e., a negative sign represents a safer than average condition) (*105*).

Sites with no sidewalks or pathways had the highest "hazard scores", with values of +2.6 (using P as the exposure measure) and +2.2 (using P x V as the exposure measure). This compared to "hazard scores" of +1.2 and +1.1 (using exposure measures of P, or (PxV), respectively) for sites with a sidewalk on one side of the road only. Sites with sidewalks on both sides of the road had "hazard scores" of -1.2 (using exposure measures of P and also P x V), which represents a safer condition than having sidewalks on one side or no sidewalks at all (*105*).

A 1988 study by Knoblauch, Tustin, Smith, and Pietrucha involved, among other things, conducting further analyses to compare hazard scores for groups of sites with sidewalks on both sides of the road vs. sites with no sidewalks (*104*). Comparisons were made separately for residential, commercial, and mixed residential areas. The lack of sidewalks was associated with much greater hazard scores (compared to sites with sidewalks) on residential streets (hazard scores of + 8.7 vs. – 1.4) as compared to sites in mixed residential areas (hazard scores of + 4.5 vs. – 1.4) and commercial areas (hazard scores of + 1.2 vs. – 1.1) (*104*).

Conclusions

Providing well-planned and properly designed sidewalks and walkways is an essential element for accommodating safe travel by pedestrians. Although the number of crash-based studies is limited on the relative effectiveness of sidewalks and walkways, there is strong evidence to support the logical assumption that having sidewalks and/or walkways along streets and highways is associated with a substantial reduction in pedestrian "walking along roadway " crashes. Furthermore, there are certain types of locations where the addition of sidewalks or walkways is likely to be particularly effective, such as on neighborhood streets and/or where there is likely to be regular pedestrian activity at night.

3.3.2. Mid-block Crossing Design and Traffic Control

Mid-block pedestrian crossings are often provided along roadway segments in response to a significant number of pedestrians crossing the road. Mid-block pedestrian crossings may have a variety of traffic control devices (i.e., pavement markings and signage).

More research is needed to quantify the effects of mid-block pedestrian crossing designs on pedestrian and motorist behaviors, as well as pedestrian crashes. In particular, there is a need to evaluate various types of crossings, such as zebra, signal-controlled (Pelican) and signalized crossings with pedestrian push-buttons and technology to extend the walk (or clearance) interval when needed for a slow-moving pedestrian (Puffin crossings). More research is also needed on overhead illuminated and flashing pedestrian signs, as well as LED "animated eyes" displays and advance stop lines (or yield lines). Finally, there is a need to evaluate a wide range of traffic calming measures on pedestrian and vehicle crashes.

Exhibit 3-127: Potential resources on the relationship between the mid-block pedestrian crossings and safety

DOCUMENT	DESCRIPTION	COMMENT
(*83*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians including the effect on pedestrian safety of crosswalks	Suggested by NCHRP 17-18(4). Added to synthesis.
(*93*) (Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Includes a discussion of pedestrian strategies and relevant research, including midblock pedestrian treatments	Referenced and some qualitative information added to synthesis.
(*106*) (Nee, J. and Hallenbeck, M. E., "A Motorist and Pedestrian Behavioral Analysis Relating to Pedestrian Safety Improvements - Final Report." Seattle, Washington State Transportation Commission, (2003))	Evaluated motorist and pedestrian behavioral changes that resulted from changes in the roadway environment, traffic enforcement activities, and a public information campaign	Limited qualitative information added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Summarizes research results from a wide variety of research topics	Not added to synthesis. No additional information on pedestrian crossing research
(*107*) (Zegeer, C. V., Stewart, R., Huang, H., and Lagerwey, P., "Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines." FHWA-RD-01-075, McLean, Va., Federal Highway Administration, (2002))	Matched comparison of 5 years of crash data at 1,000 marked crosswalks and 1,000 unmarked crosswalks	Suggested by NCHRP 17-18(4). Added to synthesis.
(*108*) (Huang, H. F. and Cynecki, M. J., "The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior." FHWA-RD-00-104, McLean, Va., Federal Highway Administration, (2001))	Evaluated the effects of selected traffic calming treatments, at both intersection and mid-block locations, on pedestrian and motorist behavior	Added to synthesis.
(*109*) (Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Summarizes research and practice related to uncontrolled crossings	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*110*) (Nitzburg, M. and Knoblauch, R. L., "An Evaluation of High-Visibility Crosswalk Treatment - Clearwater Florida." FHWA-RD-00-105, McLean, Va., Federal Highway Administration, (2001))	Before and after study with control on the effect of novel high visibility crosswalk, evaluated driver yielding, pedestrian behavior, and conflicts	Suggested by NCHRP 17-18(4) although novel system. This treatment was used at intersections, so it is referenced in the HSM chapter on intersection crossings. Limited qualitative information added to synthesis.
(Van Houten, R., Malenfant, J. E., and McCusker, D., "Advance Yield Markings: Reducing Motor Vehicle-Pedestrian Conflicts at Multilane Crosswalks with Uncontrolled Approach." Transportation Research Record, No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 69-74.)	Evaluated the effect of advance yield markings and a symbol sign on pedestrian safety at intersections; used pedestrian and motorist behavior as surrogates	Added to Chapter 4.
(Bacquie, R., Mollett, C., Musacchio, V., Wales, J., and Moraes, R., "Review of Refuge Islands and Split Pedestrian Crossovers - Phase 2." Toronto, Ontario, Canada, City of Toronto, (2001))	Evaluation in Toronto of the relative safety performance of 30 mid-block pedestrian refuge islands (PRIs) and 20 mid-block split pedestrian crossovers (SPXOs)	Focus is on median treatment. Not added to synthesis.
(*112*) (Huang, H., "An Evaluation of Flashing Crosswalks in Gainesville and Lakeland." Florida Department of Transportation, (2000))	Evaluated flashing crosswalk systems in Gainesville, FL and Lakeland, FL.	No AMFs. Added to synthesis.
(Storm, R., "Pavement Markings and Incident Reduction." Ames, Iowa, 2000 MTC Transportation Scholars Conference, (2000) pp. 152-162.)	Summarized studies on safety effects of pavement markings on pedestrian treatments at intersections	Referenced in the HSM chapter on intersection crossings. Not added to synthesis.
(Hunter, W. W. and Stewart, J. R., "An Evaluation Of Bike Lanes Adjacent To Motor Vehicle Parking." Chapel Hill, Highway Safety Research Center, University of North Carolina, (1999))	Analyzes bicyclist conflicts and behaviors on bike lanes next to parking lanes	Not added to synthesis. Information is not provided on pedestrian crossings.
(Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))	Discusses results from Australian research studies	Added to pedestrian refuges synthesis
(*114*) (Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))	Discusses research findings from pedestrian research in the U.K.	Added to synthesis.
(*115*) (Godfrey, D. and Mazella, T., "Kirkland's Experience with In-Pavement Flashing Lights at Crosswalks." Lynnwood, Washington, ITE/IMSA Annual Meeting, (1999))	Documents some initial results from 2 locations of in-pavement crosswalk lights. Developed installation criteria.	No AMFs. Added to synthesis.
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))	Summarizes pedestrian safety research and countermeasure evaluation studies	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(McMahon, P. J., Duncan, C., Stewart, D., Zegeer, C. V., and Khattak, A., "An Analysis of Factors Contributing to "Walking Along Roadway" Crashes." Washington, D.C., 78th Annual Meeting Transportation Research Board, (1999))	Analyzed pedestrian crash data at 47 crash sites and 94 comparison sites; identified the relationship between the provision of sidewalks and "walking along roadway" crashes	Not added to synthesis. Did not specifically analyze pedestrian crossings.
(Hummel, T., "Dutch Pedestrian Safety Research Review." FHWA-RD-99-092, McLean, Va., Federal Highway Administration, (1999))	Summarizes Dutch pedestrian safety research results	Not relevant to this section. Not added to synthesis.
(*116*) (Van Houten, R., Healey, K., Malenfant, J. E., and Retting, R. A., "Use of Signs and Symbols to Increase the Efficacy of Pedestrian Activated Flashing Beacons at Crosswalks." Transportation Research Record 1636, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 92-95.)	This experiment evaluated two strategies for increasing the percentage of motorists yielding to pedestrians at crosswalks equipped with pedestrian-activated flashing beacons	Limited qualitative information added to synthesis.
(Hunt, J., "A Review of the Comparative Safety of Uncontrolled and Signal Controlled Midblock Pedestrian Crossings in Great Britain." Cologne, Germany, 9th International Conference on Road Safety in Europe, (1998))	Review of performance of Pelican and Zebra crossings in Kent (U.K.).	No AMFs, conflicting results. Not added to synthesis.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Summarizes information from other research studies, with minimal mention of midblock treatments	Not added to synthesis.
(Bowman, B. L. and Vecellio, R. L., "Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety." Transportation Research Record 1445, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 169-179.)	Evaluated the safety effect of various median types on both vehicular and pedestrian safety; analyzed over 30,000 crashes; 3 cities	Suggested by NCHRP 17-18(4). Added to pedestrian refuges synthesis.
(*118*) (Kemper, B. and Fernandez, P., "Design and Safety of Pedestrian Facilities." Washington, D.C., Institute of Transportation Engineers, (1994))	Summarizes thirteen types of traffic-calming measures.	Limited qualitative information added to synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Summarized research on geometric pedestrian treatments, including overpasses and underpasses and traffic calming measures	Not added to synthesis.
(Mueller, E. A. and Rankin, W. W., "Pedestrians." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 8, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Summarizes pedestrian research prior to 1970	Not added to synthesis.

The majority of studies included in this synthesis are based on the effect on behavior of the various treatments. Limited crash analysis has been performed for mid-block pedestrian crossing treatments. Due to the limited research available, each treatment is discussed in terms of all road types that may experience pedestrian traffic. Where specific site characteristics are known they are stated.

Discussion: Use alternative crosswalk markings and traffic control devices at uncontrolled locations (Continental, Ladder, Zebra, Pelican, Puffin, and Toucan)

The MUTCD defines three types of crosswalk markings: standard parallel lines, ladder or continental stripes, and diagonal stripes (*50*).

A study by Zegeer et al. found no statistically significant difference in pedestrian crash risk for various types of crosswalk markings (standard parallel lines, ladder, zebra, or continental style) (*107*).

In his 1999 summary of pedestrian safety facilities in the United Kingdom, Davies describes several interesting variations of the crosswalk concept. The following four crosswalk marking types are typically installed at midblock crossings in the U.K. (*114*):

1. Zebra – This type of crossing is marked with black and white stripes. Pedestrians on a zebra crossing have priority over vehicles.
2. Pelican – In this type of crossing, the pedestrian pushes a button which activates a "red/green man" signal light on the far side of the road that shows the pedestrian when to cross.
3. Puffin – Created to replace the pelican crossing, the puffin is also controlled by a pedestrian push-button. However, the "red/green man" signal is located on the same side of the road as the pedestrian; and the crossing is considered "intelligent" because it monitors the presence of pedestrians waiting and crossing and can modify the amount of time provided to cross the road as needed.
4. Toucan – This type of crossing is similar to both the pelican and the puffin but is based on the concept of pedestrians and bicyclists sharing the crossing (i.e., "Two can cross").

Zebra, Pelican, Puffin, and Toucan crossings are discussed below. Pedestrian signal options commonly used in the U.S. are also discussed in Chapter 4.

Zebra crossings

According to Hunt (1998), Zebras create far less delay for pedestrians in crossing a road than Pelicans and are more cost-effective to install and maintain than their signalized counterparts (*120*). Despite these advantages, however, traffic engineers during the past decade have tended to replace Zebra crossings with Pelican crossings and to opt for Pelican crossings rather than Zebra crossings at new installations for the following reasons:

- Signal-controlled pedestrian crossings seem more consistent with increasingly signalized roadways and intersections where drivers are conditioned to stop for signals rather than other visual cues;
- Signal-controlled Pelican crossings allow for the smooth flow of vehicular traffic in areas of heavy pedestrian activity; and
- Both traffic engineers and the public seem to feel that Pelican crossings are safer because drivers are controlled by signals rather than their own discretion.

However, the tendency to replace Zebra crossings with Pelican crossings after an accident occurs has not necessarily improved either safety or convenience for pedestrians at the locations where this has been done. Some experts feel that Pelican crossings encourage drivers to rely on signals rather than watching for pedestrians. In traffic-calmed areas, Zebra crossings may be making a comeback because they give pedestrians greater priority, are less expensive, and are more visually appealing.

Davies mentions the recent installation of Zebra crossings at three busy roundabouts in downtown Edinburgh, Scotland, the first Zebra crossings to be installed in that city in 30 years (*114*). This was done because it would have been difficult to put in Pelican crossings at these particular locations, and it was felt that the Zebra crossings gave priority to pedestrians and reduced pedestrian delay. Officials are monitoring how well the Zebra crossings perform, but initial results have been favorable. It was even noted that when a long line of cars developed, pedestrians would sometimes forego their legal right-of-way and stop to allow the vehicles to pass.

There seems to be mixed results on the use of Zebra (unsignalized) and Pelican (signalized) crossings in the U.K. Although jurisdictions have often replaced or installed Pelican crossings in many towns and cities, Zebra crossings are still preferred in some situations, such as at downtown locations to reduce pedestrian and motorist delay.

Pelican crossings

The Pelican crossing was introduced in the United Kingdom in 1969 and is the main type of independent or stand-alone signal-controlled pedestrian crossing.

Davies points out that installation of a Pelican or other type of crossing does not necessarily reduce pedestrian accidents and may sometimes produce increased accidents due to increased activity or other factors (*114*). A recent study (CSS, 1997 as cited in (*114*)) found no correlation between accident rates and levels of pedestrian and vehicle flow.

Puffin crossings

Davies reports that during the 1990’s the UK DOT sponsored experiments with other types of signal-controlled crossings such as the Puffin and the Toucan (*114*). The Puffin crossing was developed to replace Pelican crossings that, according to Billings and Walsh (1991), need to be improved because Pelican crossings:

- Do not allow sufficient time for slow pedestrians to cross;
- The flashing green man phase is stressful and confusing;
- Cause unnecessary delay for vehicles when pedestrians are able to cross quickly; and
- The fixed minimum time between pedestrian phases creates excessive delay for people crossing at these locations.

Research on the newly developed Puffin crossings (Davies, 1992 as cited in (*114*)) provided sufficiently positive feedback to encourage continued development. The Puffin crossings that Davies studied had pressure-sensitive mats near the curb to detect waiting pedestrians as well as infrared sensors to adjust crossing time.

Davies also summarizes the following work on this topic (*114*). Further research on user behavior and pedestrian detection at Puffin crossings was undertaken by Reading et al. (Reading, Dickinson, and Barker, 1995). Unfortunately, some experiments on the Puffin crossings were plagued by unreliable equipment. Reading, Wan, and Dickinson (1995) looked at the potential for using computer vision-based pedestrian detection systems, which would take into account not only the presence but also the volume of pedestrians at a crossing. However, the authors of that study decided that computer systems available at that time were inadequate to the task.

Crabtree (1997) furthered the research into computer applications at Puffin crossings (as cited in (*114*)). With some of his modifications, he found that pedestrians were more likely to look at traffic rather than straight ahead (where the green man would be located on a Pelican crossing signal). Crabtree noted fewer serious crossing infringements such as crossing when vehicles had the green light, which he attributed to the reduced delay pedestrians experienced with Puffin crossings. Yet there were more of what Crabtree considered to be slight infringements such as pedestrians crossing when vehicles had the red light but the green man was no longer showing on the pedestrian signal.

In conclusion, at the time that Davies wrote his report (1999), there were over 60 Puffin test sites. In spite of equipment problems, it seemed clear that the Puffin crossing technology was superior to the Pelican crossing and more amenable to adjustment to suit the needs of various localities. At the end of 1997, regulations were passed (in the U.K.) which gave local authorities the right to install Puffin crossings without Government approval (*114*).

Toucan crossings

The 1980s saw development of a parallel signal-controlled type of crossing for pedestrians and cyclists. However, this approach was expensive and took up more space. In 1989, Trevelyan and Ginger found no safety or practical issues for pedestrians where cyclists were allowed to ride over Zebra or Pelican crossings. This led to the design of a shared type of crossing: the Toucan (Morgan, 1993), with a red man/green man and a green bicycle on a single far-side pole. The Toucan signal is operated by a push-button and often has an additional vehicle actuation for pedal cycles. At the time of Davies' report (1999), there were over 200 Toucan crossings in the UK, even though they required special authorization (*114*). Some of the crossings feature infrared on-crossing detection and nearside aspects, like the Puffin crossing does. Taylor and Halliday (1997) have done more recent studies of various technical and user issues for the Toucan crossings. Responses from pedestrians and cyclists using the Toucans were favorable, in spite of problems with equipment reliability (*114*). Future versions of the Toucan will probably resemble the Puffin but will include cycle aspects.

Discussion: Experimental measures at uncontrolled mid-block crossings

In 1971, Malo et al. studied innovative safety devices installed at thirteen pedestrian crossings in Detroit, Michigan that had either a history of crashes or what was felt to be an unusual hazard (as cited in (*83*)). Various types of signing, marking, lighting, and pedestrian signal actuation were evaluated. Prior to the study, a major effort was made to publicize the upcoming changes and educate the public. Approach speeds, gaps, volumes, driver response, pedestrian attributes, gap acceptance, and behavior were measured. Drivers and pedestrians were interviewed to determine their opinions about the site modifications. According to Campbell et al., Malo found that (*83*):

- After the safety devices were installed, there was a statistically significant increase in crosswalk usage, especially during the daytime.
- There was no substantial change in the speed distribution of free-flow vehicles in the area near the crosswalk.
- More drivers slowed down in response to pedestrians waiting to cross.
- Pedestrians used the push buttons more often, but not as much as anticipated.

- Although drivers who were surveyed expressed satisfaction with the safety devices, pedestrians were not content with driver response. Pedestrians thought that motorists would slow down when a device was actuated, but drivers did not expect to slow down much or to stop unless there was a traffic signal or stop sign.

A 2001 report entitled "Alternative Treatments for At-Grade Pedestrian Crossings" (*109*) contains a discussion of experimental measures used at uncontrolled crossings. However, the effectiveness of these devices on pedestrian crash rates in real situations is unknown.

Treatment: Install raised pedestrian crosswalks

Rural two-lane roads; Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

Not applicable.

Urban and suburban residential two-lane roads

Raised pedestrian crossings tend to be applied most often on business streets, in an urban environment. These streets would usually be two-lane roadways. Raised pedestrian crossings are applied both at intersections and midblock. The results presented include both cases, as most studies do not state whether the crossings were at intersections or midblock.

Four studies have been found, that have evaluated the safety effects of raised pedestrian crossings. These studies contain a total of ten estimates of effect. None of the studies have controlled for regression-to-the-mean or long-term trends in accident occurrence. For raised pedestrian crosswalks, 8 estimates have been rated as low quality and 2 as medium low quality. Thus, a high quality quantification of safety is not available for this measure.

The safety effects of raised pedestrian crosswalks in Exhibit 3-128 refer to pedestrian accidents or accidents involving motor vehicles only. The latter category includes all accidents that involve one or more motor vehicles, but not a pedestrian. It cannot be ruled out that the summary estimates presented in Exhibit 3-128 are confounded by uncontrolled regression-to-the-mean and uncontrolled long-term trends in accident occurrence. Standard errors have been adjusted by a factor of 3 for each low quality estimate of effect and a factor of 2.2 for each medium low quality estimate of effect.

Exhibit 3-128: Effects on injury accidents of raised pedestrian crosswalks (8)

Author, date	Treatment/ Element	Setting	Road type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	All accidents, Injury	0.642	0.543
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	Pedestrian accidents, Injury	0.545	0.937
Elvik and Vaa, 2004	Install raised pedestrian crosswalk	Urban and suburban	Residential two-lane roads, volume not reported	Vehicle accidents, Injury	0.697	0.667

Raised pedestrian crossings appear to reduce both pedestrian accidents and vehicle accidents. There are few studies and these have not controlled adequately for potentially confounding factors. The adjusted standard errors are of the same magnitude as the summary estimate of effect, indicating that there is very large uncertainty in these estimates. Despite this, it is not implausible to believe that raised pedestrian crossings do reduce accidents, since they reduce speed.

Huang and Cynecki looked at how various traffic-calming techniques affected the behavior of pedestrians and drivers at midblock and intersection locations in seven states in the U.S. (*108*). Traffic-calming devices resulted in lower overall vehicle speeds. Combining a raised crosswalk with an overhead flasher increased motorist yielding behavior, although it was not possible to separate the relative effect of the two aspects of this modification. No other treatments significantly changed the percentage of pedestrians for who the drivers yielded. The various traffic-calming measures did not produce a statistically significant effect on average pedestrian waiting time. It was found that refuge islands channelized people into marked crosswalks and that a raised intersection in one location had the same effect.

Raised pedestrian crossings appear to reduce both pedestrian accidents and vehicle accidents. There are few studies and these have not controlled adequately for potentially confounding factors. The adjusted standard errors are of the same magnitude as the summary estimate of effect, indicating that there is very large uncertainty in these estimates. Despite this, it is not implausible to believe that raised pedestrian crossings do reduce accidents, since they reduce speed.

Discussion: Install pedestrian-activated flashing yellow beacons only

Pedestrian-activated yellow beacons are sometimes used to alert motorists that pedestrians are crossing the roadway. Research has shown that overhead pedestrian signs with flashing beacons do encourage motorists to yield for pedestrians more often (*110*,*121*,*122*). These positive effects, however, are modest because 1) yellow warning beacons are not exclusive to pedestrian crossings, so drivers do not necessarily expect a pedestrian when they see a flashing beacon; and 2) motorists learn that many pedestrians are able to cross the road more quickly than the timing on the beacon allows and therefore may think the person has already finished crossing the road if a yielding or stopped car blocks the pedestrian from sight.

In 1976, Braaksma evaluated the safety, delay, aesthetics, and cost of “special crosswalks” in five major Canadian cities (as cited by (*83*)). In Calgary, standard crosswalk markings were used, but the system featured an overhead “PEDESTRIAN” sign with a large “X” and 8 inch amber flasher units on either side of the word, plus a smaller flasher below it that the pedestrian could see. A sign next to the activation button advised pedestrians to push it and to use caution in crossing the street. A roadside sign located 150 to 250 ft prior to the crosswalk read “WHEN LIGHT FLASHING – MAXIMUM 20 (KPH) – DO NOT PASS – HERE TO CROSSWALK”. The flasher above this sign was also activated by the pedestrian button (*83*). There are no quantified effects of this treatment.

Discussion: Install pedestrian-activated flashing yellow beacons and extra pavement markings in advance of crosswalks

In 1976, Braaksma evaluated the safety, delay, aesthetics, and cost of “special crosswalks” in five major Canadian cities (as cited by (*83*)). “Special crosswalks” reviewed in this study were those with extra features like overhead signs and lighting, pedestrian-activated flashing yellow beacons, pavement markings, parking prohibitions, or special laws. In Toronto, each traffic lane was marked with a large white “X” 100 ft in advance of the crosswalk and a standard advanced pedestrian crossing warning sign was installed on the roadside nearby. The “X” was 20 ft long, with each of its lines being 12 to 20 inches wide. The crosswalk itself was no less than 8 ft wide with edgelines of 6 to 8 inches in width (*83*).

Pedestrian fatalities decreased in Toronto after installation of the system described above. However, two hazardous behavior patterns emerged. Some pedestrians would step off the curb without signaling to drivers that they intended to cross the road, perhaps assuming that cars would stop instantaneously. Also, it was observed that motorists initiated overtaking maneuvers just prior to the crosswalk, which suggests a need for improved education and enforcement (*83*).

Discussion: Install illuminated crosswalk signs

Campbell et al. note a before- after study conducted on 20 sites in Tokyo, Japan, where illuminated crosswalk signs were installed (*83*). Pedestrian crashes increased by 4.8% and other crashes went up 2.4% in 218 yard (200 m) sections on either side of the installation. In 55 yard (50 m) sections, both pedestrian and other types of crashes increased 11.4%. The authors concluded that the illuminated crosswalk signs were not effective in reducing crashes, although the reason for the crash increase may be related to factors such as increased volumes or other confounding factors.

Discussion: Install overhead electronic LED signs

Overhead electronic LED pedestrian signs that show motorists which direction the pedestrian is crossing from and remind the driver to look out for pedestrians are effective in increasing driver yielding behavior (*106,116*). These signs have animated eyes that instruct motorists to watch for pedestrians coming from a particular direction. There is no known safety evaluation of this treatment.

Van Houten et al. evaluated two strategies for increasing the percentage of motorists yielding to pedestrians at crosswalks equipped with pedestrian-activated flashing beacons. One strategy involved adding an illuminated sign, with the standard pedestrian symbol next to the beacons. The second strategy involved placing signs 50 m before the crosswalk that displayed the pedestrian symbol and requested motorists to yield when the beacons were flashing. Both interventions increased yielding behavior and the effect of both together was greater than either alone. However, only the sign requesting motorists to yield when the beacons were flashing was effective in reducing motor vehicle-pedestrian conflicts (*116*). This is probably due to the following: 1) electronic signs display the actual pedestrian symbol when someone is in the crosswalk, so these signs are associated with pedestrian activity rather than other traffic situations; 2) by showing which direction a person is crossing, the electronic sign alerts the driver to look vigilantly in the appropriate direction; and 3) the electronic sign also lets drivers know when pedestrians are crossing from both directions simultaneously (*116*).

Discussion: Install in-pavement lighting at uncontrolled locations

In-pavement lighting is sometimes used to alert motorists to the presence of a crosswalk at uncontrolled locations. Both sides of the crosswalk are lined with encased raised pavement markers, which sometimes contain LED strobe lighting. In-pavement lighting has shown positive results (such as increase driver compliance, motorists yielding to pedestrians) in Washington State but not in Florida {Huang, 2000 3345 /id;Godfrey, 1999 3344 /id}.

There are several drawbacks to this method. For example, the whole system must be replaced whenever road surfacing or utility repairs occur. Also, in-pavement lights are generally visible to only the first car in a platoon. Headlights from oncoming traffic may obscure a driver's view of the entire crossing. Furthermore, in-pavement lighting does not indicate the direction of a pedestrian's travel or if people are crossing simultaneously from both sides of the road. Finally, the in-pavement flashers may be difficult to see during bright daylight hours.

The available studies on in-pavement flashing lights provided no data from which to derive AMFs. Much more evaluation is needed to fully understand the effects of in-pavement flashing lights (at uncontrolled locations) on traffic, pedestrian behavior, and pedestrian safety for a variety of traffic volumes, vehicle speeds, light conditions (day vs. night), number of lanes, and other factors.

Discussion: Reduce posted speed through school zones during school times

In 1978, Zegeer and Deen evaluated the "25 MPH WHEN FLASHING" sign at 48 school zone locations with yellow flashing beacons in Kentucky (as cited in (*83*)). Speeds ranged from 35 to 45 mph (56 to 72 km/h) without the flasher. Only 18% of all motorists complied with the 25 mph speed limit during times when the flashers were activated. Overall vehicle speeds averaged just 3.6 mph less during flashing periods than during times when the flashers were off, and only two sites experienced average speed reductions of 10 mph or more. The researchers concluded that the regulatory flashing signs were not effective in reducing vehicle speeds to the mandated 25 mph. In rural locations, the flashers increased speed variance, which elevated the potential for rear-end crashes. School crossing guards and police enforcement did promote driver compliance with speed limits (*83*). Additional information on treatments for school zones will be included in Section 3.3.5 School Routes and School Zones, in a future HSM edition.

Treatment: Provide pedestrian overpasses and underpasses

All road types

Exhibit 3-129 shows the results of a before- after comparison of pedestrian crashes made at 31 locations in Tokyo, Japan, where pedestrian overpasses had been installed (as cited in (*83*)). Crashes occurring in 200 m (218 yard) and 100 m (109 yard) sections on either side of each site were tabulated. After overpasses were installed, pedestrian crossing accidents decreased substantially, although non-related accidents increased by 23% in the 200 m sections. It is not known whether this increase could have been the results of other factors unrelated to the overpass. The researchers also found that daytime pedestrian crashes were reduced more than nighttime ones by the installation of pedestrian overpasses (*83*). This may be related to the volumes of pedestrians crossing the road. No other details about the site characteristics were reported. Standard errors could not be developed for these values.

Exhibit 3-129: Comparison of crashes before and after installation of pedestrian overpasses (Tokyo, Japan) (83)

Type of Crash	200 m sections			100 m sections		
	Before	After	Index of Effectiveness	Before	After	Index of Effectiveness
Pedestrian crossing crashes	2.16	0.31	0.144	1.81	0.16	0.088
Non-pedestrian	2.26	2.77	1.23	1.65	1.87	1.133

crossing crashes						
Total	4.42	3.09	0.699	3.46	2.03	0.567

The amount of use of a pedestrian overpass by pedestrians is one measure of its effectiveness. According to Moore and Older (1965), that usage depends on walking distances and how convenient the overpass is for potential users (as cited in (*83*)). Moore and Older developed a measure of convenience (R), defined by the ratio of the time it took to cross the street on an overpass divided by the time it took to cross at street level. According to this study, about 95% of pedestrians opt for the overpass if R=1, meaning that it takes the same amount of time to cross using the overpass as it does at street level. If the overpass route takes 50% longer (R=1.5), almost no one uses it. For similar values of R, the use of underpasses by pedestrians was not as high as for overpasses (*83*).

Overpasses can present certain problems for pedestrians, as suggested by a panel of disabled residents commenting on three pedestrian overpasses in San Francisco (Swan, 1978 as cited in (*83*). Potential hazards or barriers include: inadequate or nonexistent railings on bridge approaches; steep cross slopes; lack of a level platform at the base on bridge ramps where wheelchairs can stop prior to entering the street; inadequate sight distance to see opposing flow of pedestrians and also lack of level rest areas on spiral ramps; maze-like barriers on bridge approaches which are used to slow down bike traffic but can also impede the progress of wheelchair-bound or visually impaired users; and lack of sound screening on the overpass so that the visually impaired can hear people coming the other way and avoid crashes (*83*).

Templer et al. (1980) evaluated the accessibility of 124 existing overpasses and underpasses (as cited in (*83*)). Eighty-six percent of the structures had at least one major barrier to physically handicapped pedestrians. Among the obstacles were: no ramps (only stairs) leading to the crossing; ramps that were too long or steep; actual physical barriers that blocked the access paths; too narrow sidewalk on the overpass or underpass; and steep cross slopes. Templer et al. suggested solutions to these obstacles and provided a cost-effective comparison of the various options presented. The Americans with Disabilities Act (*99*) required gentler slopes to be used on approaches to crossing structures, which has enhanced accessibility for wheelchair users and bicyclists, but the resultant lengthening of ramps has also been found to discourage use of the facilities. On the other hand, devices such as fencing are sometimes employed to channel pedestrians toward overpasses and underpasses.

In the end, grade-separated crossings are very expensive structures and may not be used by pedestrians if not perceived as safer and more convenient than their street-level counterparts.

Discussion: Apply traffic calming measures on residential streets

The purpose of traffic calming is to reduce vehicular volumes and speeds on residential streets, which, in turn, promotes a more pedestrian-friendly environment. Thirteen types of traffic-calming measures were listed in a 1994 ITE document (*118*). Those measures were: street closures, cul-de-sacs, diverters, traffic circles, woonerfs, chicanes, flares/chokers, speed humps, speed limit signs and speed zones, speed watch and enforcement programs, walkways, parking controls, and other signage.

Huang and Cynecki looked at how various traffic-calming techniques affected the behavior of pedestrians and drivers at midblock and intersection locations in seven states in the U.S. (*108*). Traffic-calming devices resulted in lower overall vehicle speeds. Combining a raised crosswalk with an overhead flasher increased motorist yielding behavior, although it was not possible to separate the relative effect of the two aspects of this modification. No other treatments significantly changed the percentage of pedestrians for who the drivers yielded. The various traffic-calming measures did not produce a statistically significant effect on average pedestrian waiting time. It was found that refuge islands channelized people into marked crosswalks and that a raised intersection in one location had the same effect.

The safety effects of traffic calming on roadway segments and at intersections are discussed in Section 3.2.6 and Chapter 4, respectively.

The Transport and Road Research Laboratory of Great Britain developed the concept of speed humps, also known as road humps, undulations, or "sleeping policemen", which are intended to reduce traffic speeds to 20 to 25 mph. A speed hump extends across the full width of the road and has a rounded surface, while the speed table is flat-topped. Speed tables are sometimes used in conjunction with crosswalks and can be built with brick pavers. Speed tables are more often found in Europe and Australia than in the U.S. Speed humps are further discussed in Section 3.2.6.

Summary

In terms of the effects of mid-block pedestrian crossing design, research in Great Britain has found that replacing zebra (un-signalized) crossings with Pelican (signal-controlled) crossings does not necessarily reduce pedestrian crashes, although the precise effects are not well established for various conditions. A Puffin crossing is signalized with a pedestrian push button and the red/green man symbol on the same side of the street as the pedestrian, and the signal considered "intelligent" because it can modify the amount of crossing time provided for a pedestrian to cross the road as needed. Of the 60 Puffin test sites in Great Britain, they were determined to be superior to the Pelican crossings, although crash effects were not documented.

Some types of overhead flashing signs have been found to improve motorist yielding to pedestrians on low-speed, two-lane roads. An overhead, electronic LED pedestrian sign ("animated eyes" display, which shows the direction that the pedestrian is coming from) has shown promising results in terms of improved motorist yielding to pedestrians. This was particularly effective when yield signs and/or markings were placed 50 m before the crosswalk. Flashing "25 mph When Flashing" signs in school zones have been found to significantly reduce vehicle speeds in school zones but did not reduce speeds to the 25 mph speed limit. However, school crossing guards and police enforcement were much more effective in reducing vehicle speeds than the regulatory speed limit signs alone.

Pedestrian overpasses and underpasses can be effective in reducing pedestrian crashes in certain locations. However, grade-separated crossings are very expensive structures and may not be used by pedestrians if not perceived to be safer and more convenient than crossing at street level. There are various types of speed management measures that can also successfully slow down vehicle speeds and therefore have a positive effect on pedestrian safety. Such measures include street closures, diverters, traffic circles, chicanes, speed humps, speed tables, speed zones, and others. Many of these measures have shown to reduce vehicle speeds along streets, but there is limited information on the effects on pedestrian crashes.

3.3.3. Pedestrian Refuges

According to the AASHTO Guide, a highway median is defined as: "the portion of a divided highway separating the traveled way for traffic in opposing directions" (*26*). In terms of motor vehicle safety, the benefits of separating opposite-direction traffic are obvious. Medians and islands can also enhance pedestrian safety because they provide a place of refuge for people crossing the street, whether at an intersection or midblock. With a median or refuge island available, pedestrians initially only have to concentrate on traffic coming from their left. After reaching the median/island, they can wait for an acceptable gap in traffic to the right before continuing to cross the road. Medians may be painted on the pavement, or the median may be raised with curbs.

If properly planned, medians and islands provide space for landscaping that can enhance the character of a street and also help to reduce vehicular speeds. However, landscaping should be installed and maintained so as not to block sight distance between motorists and pedestrians. Vehicle turning movements must also be taken into account, with medians designed to discourage U-turns and unwanted through traffic on residential streets. Installation of a median also necessitates proper design and placement of other cross-sectional elements such as sidewalks and planting strips, bike lanes, curb ramps, travel lane widths, roadside plantings, and other features (*93*).

The following is a discussion of literature pertaining to medians and refuge islands along roadway segments.

Exhibit 3-130: Resources examined for the relationship between pedestrian refuge islands (medians) and safety

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Compilation of research effectiveness information and other details of a wide range of pedestrian treatments, including medians and refuge islands.	No AMFs. Not added to synthesis.
(Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians and pedestrian facility effectiveness, including the effect of sidewalks on pedestrian safety.	Identifies potential resources. Not added to synthesis
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Synthesis of past research of several treatments.	No new information. Not added to synthesis.
(*107*) (Zegeer, C. V., Stewart, R., Huang, H., and Lagerwey, P., "Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines." FHWA-RD-01-075, McLean, Va., Federal Highway Administration, (2002))	Primarily intended to determine the safety effects of marked vs. unmarked crosswalks on pedestrian crashes	AMFs for raised medians on multilane roads added to synthesis.
(*123*) (Bacquie, R., Egan, D., and Ing, L., "Pedestrian Refuge Island Safety Audit." Monterey, Calif., Presented at 2001 ITE Spring Conference and Exhibit, (2001))	Comprehensive safety review of pedestrian refuge islands in Toronto, Canada, assessing collision history, human factors aspects, design, and operational characteristics.	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Huang, H. F. and Cynecki, M. J., "The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior." FHWA-RD-00-104, McLean, Va., Federal Highway Administration, (2001))	Includes a before/after operational evaluation of 5 intersections where refuge islands were added in Corvallis, Oregon and Sacramento, California.	Discussed under Pedestrian and bicycle intersections-refuge islands. Not added to synthesis.
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Includes a synthesis of research and practice related to roadway treatments at-grade pedestrian crossings.	Discussed under Pedestrian and bicycle intersections-refuge islands. Not added to synthesis.
(*113*) (Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))	Compiled results of pedestrian safety research in Australia including summary of studies that investigated effects of medians and refuge islands	Conclusions added to synthesis. No AMFs.
(McMahon, P. J., Duncan, C., Stewart, D., Zegeer, C. V., and Khattak, A., "An Analysis of Factors Contributing to "Walking Along Roadway" Crashes." Washington, D.C., 78th Annual Meeting Transportation Research Board, (1999))	The study analyzed pedestrian crash data at 47 crash sites and 94 comparison sites; identified the relationship between the presence of sidewalks/walkways and "walking along roadway" pedestrian crashes.	Not a research source for median/refuge island effects (nearly all sites are 2-lane). Not added to synthesis.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	This study provides recommendations based on a synthesis of information from other studies.	Identifies other potential sources. Not added to synthesis.
(*117*) (Bowman, B. L. and Vecellio, R. L., "Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety." Transportation Research Record 1445, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 169-179.)	Evaluated the safety effects of various median types on vehicular and pedestrian safety; analyzed over 30,000 crashes in Phoenix, Los Angeles, and Atlanta.	Conclusions added to synthesis. No AMFs.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Summary report based on a critical review of literature on safety effects of various pedestrian and bicycle treatments. Refers to Bowman study, which was underway.	Refers to other pedestrian safety studies. Not added to synthesis.
(Garder, P., "Pedestrian Safety at Traffic Signals." Accident Analysis and Prevention, Vol. 21, No. 5, Oxford, N.Y., Pergamon Press, (1989) pp. 435-444.)	Study of intersections in Stockholm and Malmo, Sweden where refuge islands were installed. The study includes an analysis of pedestrian crash data and behavioral data.	Discussed under Pedestrian and bicycle intersections-refuge islands. Not added to synthesis.
(*119*) (Lalani, N., "Road Safety at Pedestrian Refuges." Traffic Engineering & Control, Vol. 18, No. 9, London, United Kingdom, Hemming Information Services, (1977) pp. 429-431.)	Before and after studies of the effect of pedestrian refuges on crashes: sites in London	Added to synthesis.
(Mueller, E. A. and Rankin, W. W., "Pedestrians." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 8, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Synthesis of pedestrian safety literature as of 1970, but does not include any reference to studies on medians.	Not added to synthesis.

Treatment: Install raised medians at marked and unmarked crosswalks

All road types

A study by Zegeer, Stewart, Huang, and Lagerwey for FHWA in 2002, was primarily intended to determine the safety effects of marked vs. unmarked crosswalks on pedestrian crashes (*107*). This FHWA study involved the collection and analysis of data at 1,000 marked crosswalk sites and 1,000 unmarked crosswalk comparison sites in 30 U.S. cities. All of the sites were at uncontrolled approaches; that is, none of the sites had stop signs or traffic signals facing the crosswalks for approaching vehicles. Sites included midblock as well as intersection locations under a variety of traffic and roadway situations. For each site, data were collected on pedestrian exposure, traffic volume, number of lanes, median type, speed limit, and other site features, along with five years of pedestrian crash data. Poisson and negative binomial regression models were used to quantify the effects of various traffic and roadway features on pedestrian crashes (*107*).

In addition to determining the effects of crosswalk markings, number of lanes, and other roadway features (as discussed earlier), Zegeer et al. found that the presence of a raised median or crossing island was associated with a significantly lower rate of pedestrian crashes on multi-lane roads (having either marked or unmarked crosswalks). Specifically, comparing urban or suburban multi-lane roads (i.e., roads with 4 to 8 lanes) with ADT of 15,000 veh/day and above and marked crosswalks, the pedestrian crash rate (i.e., pedestrian crashes per million crossings) was 0.74 with a raised median, compared to 1.37 for sites without a raised median. Thus, having a raised median was associated with a 46% (i.e., 1.37 - 0.74 divided by 1.37) reduction in pedestrian crashes, compared to sites without a raised median. (Exhibit 3-131) (*107*). These results were used to develop an AMF of 0.54. The standard error of this value was calculated using Hauer's Eqn 7.3 (*54*), and applying a method correction factor of 5 (Exhibit 3-131).

For similar sites (multi-lane with ADT above 15,000 veh/day) at unmarked crosswalk locations, the pedestrian crash rate was 0.17 with a raised median, compared to 0.28 for sites without a raised median. Thus, having a raised median was associated with a 39% reduction (0.28 - 0.17 divided by 0.28) in pedestrian crash rate, compared to sites without a raised median (*107*). These results were used to develop an AMF of 0.60. The standard error of this value was calculated using Hauer's Eqn 7.3 (*54*), and applying a method correction factor of 5 (Exhibit 3-131). This standard error is larger due to the fewer pedestrian crashes observed at unmarked crosswalks with a raised median.

Furthermore, multi-lane road sites that had a center two-way-left-turn lane (TWLTL) or painted (but not raised) median did not correspond to safety benefits to pedestrians, compared to multi-lane roads with no medians at all. Thus, this study found that raised medians clearly provide a significant safety benefit to pedestrians on multi-lane roads, particularly on such roads with ADT above 15,000 veh/day (*107*).

Exhibit 3-131: Safety effectiveness of raised medians on pedestrian crashes on segments

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Zegeer et al., 2002	Raised median with marked crosswalk (uncontrolled)	Urban or suburban	4 to 8 lanes, 15,000 veh/day or more	Pedestrian crashes, all severities	0.54	0.48
Zegeer et al., 2002	Raised median with unmarked crosswalk (uncontrolled)	Urban or suburban	4 to 8 lanes, 15,000 veh/day or more	Pedestrian crashes, all severities	0.61	2.02

NOTE: The Zegeer et al., 2002, study included some 3 lane roadways, however the effects of refuge islands on 3-lane roads is less clear and not as well documented; therefore this AMF is relevant for 4 to 8 lane roads.

Treatment: Install pedestrian refuge islands or split pedestrian crossovers

All road types

A study by Bacquie et al. (2001) involved an evaluation in the City of Toronto, which compared the relative safety performance of 30 mid-block pedestrian refuge islands (PRIs) and 20 mid-block split pedestrian crossovers (SPXOs) (*123*).

The following is a specific description of the two safety devices examined by Bacquie et al. (*123*):

- Raised pedestrian refuge islands (PRIs) are approximately 1.8 meters wide and 11 meters long, located in the center of roads that are 16 meters wide. Pedestrian warning signs alert approaching motorists, with further guidance provided by end island markers and keep right signs posted at both ends of the island. Pedestrians who use the islands are advised with "Wait for Gap" and "Cross Here" signs. Pedestrians do not have the legal right-of-way.
- Split pedestrian crossovers (SPXOs) are a traffic control device unique to Ontario and described in its MUTCD. In addition to providing a refuge island, the SPXO combines static traffic signs, an internally illuminated overhead "pedestrian crossing" sign, and pedestrian-activated flashing amber beacons. Motorists approaching an activated SPXO must yield the right-of-way to the pedestrian until the pedestrian clears the driver's half of the road and reaches the island. Like the pedestrian refuges described above, SPXOs include pedestrian warning signs, keep right signs, and end island markers to guide motorists; however, the pedestrian signing reads, "Caution Push Button to Activate Early Warning System".

Exhibit 3-132 shows a direct comparison of the safety performance of these two devices. As the table indicates, the SPXO locations had a frequency of total crashes which was 5.5 times higher than the pedestrian refuge islands, perhaps accounted for in part by pedestrian volumes that averaged four times higher at the SPXOs.

*Exhibit 3-132: Safety Performance of Pedestrian Devices in Toronto (*123*)*

Traffic Control	Average Crashes per Location (crashes/year) (all crash types)	Crash Severity (%)		
		Fatal	Injury	PDO
PRI	0.67	3	42	55
SPXO	3.63	1	47	52

Exhibit 3-133 shows the types of crashes occurring at each location and suggests that refuge islands are associated with more vehicle-island crashes, while SPXOs are associated with more vehicle-vehicle accidents.

*Exhibit 3-133: Types of Crashes at Pedestrian Refuge Islands and Split Pedestrian Crossovers (*123*)*

Location	Frequency of Crash Types (and percent)			
	Vehicle-Vehicle	Vehicle-Pedestrian	Vehicle-Island	Other
PRI	5 (8%)	6 (10%)	47 (80%)	1 (2%)
SPXO	148 (68%)	35 (16%)	28 (13%)	6 (3%)

Bacquie et al. (2001) also conducted a before-after study to evaluate the safety effectiveness of pedestrian refuge islands (*123*). Pedestrian accidents that could have been prevented by a PRI were reduced at 28 sites for which data was available from 22 in the three years before installation to 6 during the three years after installation of the PRIs. However, there were 46 vehicle-island crashes during the after period (these were not possible during the three years prior to island installation). The study authors concluded that pedestrian safety had been enhanced by addition of the islands (73% reduction in mid-block pedestrian crashes or index of effectiveness of 0.27), but overall safety as reflected in crash frequency had decreased (136% increase in total crashes or index of effectiveness of 1.36). It was noted that the decrease in safety related to vehicle-island crashes might be helped by better island design and lane alignment (*123*). It is likely that the sites where PRI were implemented were selected based on accident history. Therefore, regression-to-mean is a likely factor. This study does not provide conclusive evidence for an AMF.

A before-after analysis was not conducted by Bacquie et al. for the SPXO locations (pg 19) (*124*).

Results of some studies have suggested that the safety benefits of refuge islands are debatable. In the 1994 Australian Geoplan study, as reported by Cairney in 1999, none of the four types of refuge islands examined was found to be very effective from a safety perspective. In fact, three of the types caused large increases in the adjusted pedestrian crash rate (the calculation of and adjustments made to the pedestrian crash rate were not reported), while only one type resulted in a slight reduction (2% reduction) (*113*). However, according to Cairney, "…it seems inherently unlikely that pedestrian refuges did not reduce crashes. The method used in the Geoplan study compared crashes occurring at the site of the facility, before and after. Where pedestrian refuges are provided, it would be expected that pedestrians would be attracted to cross at this point – pedestrians who would otherwise have crossed some distance along the road, so that pedestrian flow is greatly increased at the refuge. A study of the crash history of the whole street where pedestrian refuges have been installed would therefore be necessary to determine whether there had been a reduction in pedestrian crashes".

Lalani also determined that (*119*):

- At intersections, vehicular collision frequency was significantly reduced only when the refuge islands were reinforced with hatch markings to channelize motor traffic;
- At midblock locations, vehicular accidents were only reduced where the islands had internally illuminated bollards; and
- Pedestrian accidents were only reduced at sites where the refuge islands were constructed on roads next to high pedestrian generators. (It is unclear if this statement applies to intersection or midblock or both.)

As Cairney suggested with regard to the Australian research by Geoplan described earlier, it is possible that the results of the Lalani study (i.e., the increase in pedestrian crashes after installation of refuge islands) may be a manifestation of the fact that more pedestrians are drawn to use the crossing after a refuge island is installed. A study of all of the pedestrian crashes along a road section (with corresponding pedestrian exposure) and controlling for pedestrian exposure at the crossings would allow for quantifying this effect.

Discussion: Effect of median type on pedestrian safety

A 1994 study by Bowman and Vecellio was conducted to determine the effects of urban and suburban median types on the safety of vehicles and pedestrians (*117*). The study involved an analysis of 32,894 vehicular crashes and 1,012 pedestrian crashes that occurred in three U.S. cities (Atlanta, Georgia; Phoenix, Arizona; and Los Angeles/Pasadena, California). The median types which were compared were: (a) raised, (b) flush or two-way-left-turn-lane (TWLTL), and (c) no existing median (undivided). A variety of statistical tests were used, including t-tests, analysis of variance, and the Scheffe multiple comparison test. The authors did not have pedestrian volume data, but used area type (CBD and suburban areas) and land use as surrogate measures for pedestrian activity and developed pedestrian crash prediction models separately for the two area types(*117*).

The results of this analysis provide evidence that having some area of refuge (either a raised median or TWLTL) on an arterial CBD or suburban street provides a safer condition for pedestrians than having an undivided road (i.e., with no refuge for pedestrians in the middle of the street) (*117*). Furthermore, while this study found that suburban arterial streets with raised-curb medians had lower pedestrian crash rates, as compared to TWLTL medians, this difference was not statistically significant. This may be a clear indication that some refuge area (in the middle of wide streets) is more beneficial to pedestrian safety when crossing streets than having no refuge area. However, the safety benefits for a raised median vs. a TWLTL were not quantified in this study (*117*). Based on the study results, Bowman and Vecellio suggest that in CBD areas, whenever possible, divided cross-sections should be used due to their lower crash rates for pedestrians and motor vehicles.

A 1999 study by Cairney compiled the results of pedestrian safety research in Australia and included a summary of studies that investigated the effects of medians and refuge islands (*113*). Cairney cites the following studies related to medians:

- A study by Moore and McLean (125) which reports early research in New South Wales by Johnson in 1962 (126) and Leong in 1970 (127). These studies found that providing narrow medians reduced vehicle-to-vehicle crashes but had no effect on pedestrian crashes. The author did not report the sample size of the studies, the type of statistical analysis, or whether data variables such as pedestrian exposure were collected and controlled for. Accident data were not reported.
- A 1986 study by Scriven in Adelaide, South Australia (128), found that medians were effective in reducing pedestrian crashes. On arterial roads, pedestrian crash rates were directly related to median width. Roads with the narrowest (4 ft, 1.2 m) medians had pedestrian crash rates that were four times higher than routes with the widest (10 ft, 3.05 m) medians.
- A 1994 study by Claessen and Jones (129) found that replacing a 6 ft (1.8 m) painted median with a wide raised median reduced pedestrian crashes by 23 percent. According to Cairney, this conclusion was consistent with Scriven's finding that pedestrian crash rates for roads with 10 ft (3.05 m) medians were 33 percent lower than for roads with 4 ft (1.2 m) painted medians (128).

Summary

Studies from the U.S. and Australia were found in the literature that analyzed the safety effects of medians which may be used for pedestrian refuge on roadway sections. There is clear evidence that on multi-lane roads (i.e., 4 or more lanes), the presence of a median (either raised median or flush median) is associated with a significant reduction in pedestrian crashes when compared to an undivided road. In fact, pedestrian crashes were found in one major U.S. study to be associated with approximately a 40% reduction when raised medians are installed (compared to having no raised median) on multi-lane roads having ADT of 15,000 veh/day or higher (*107*).

Having a flush median on a multi-lane road does not appear to provide as much safety to pedestrians as having a raised median, based on research in the U.S. and Australia. Although a limited number of research studies are included herein which investigated the safety effects of medians on pedestrian crashes, there are several additional studies that have analyzed the safety effects of crossing islands (pedestrian refuge islands) at intersections. These studies are discussed in detail in Section 4.3.

3.3.4. Bicycle Routes

Guidelines for the planning, design, and operation of bicycle facilities are provided in the 1999 "Guide for the Development of Bicycle Facilities" report by AASHTO (*130*). Specific design information is given in that document on shared roadways (e.g., lane width, on-street parking pavement surface quality), signed shared roadways (e.g., designing sidewalks as bikeways, signing), bike lanes (e.g., bike lane widths, bike lanes at intersections and driveways), and shared use paths (e.g., widths and clearances, design speed, horizontal alignment, grades, signing and marking, lighting). Other design considerations are given on such topics as bikes on freeways, interchange areas, roundabouts, traffic signals, bike parking facilities, and accessibility requirements.

A bicycle lane (BL) is defined as a part of the roadway designated for bicycle traffic and separated from motor vehicles in adjacent lanes by pavement markings. Most often, bike lanes are installed near the right edge of the road, although they are sometimes placed to the left of right-turn lanes or on-street parking.

The 1994 FHWA report entitled *Selecting Roadway Design Treatments to Accommodate Bicycles* suggests the installation of BLs in areas with a primarily inexperienced cyclist population (*131*). The authors of that report offer a list of factors to consider when choosing safety countermeasures aimed at bicycle traffic, including:

- Defining the types of bicyclists ("design bicyclists") expected to use the facility;
- Type of roadway;
- Traffic volume;
- Average motor vehicle operating speeds;
- Traffic mix;
- On-street parking;
- Sight distance; and
- Number of intersections and entrances.

The reader may wish to refer to this and other documents for further guidance on the design and traffic control elements of bicycle facilities on roadway segments.

This section provides information on the safety effects of various types of bicycle facilities on roadways segments, such as bike lanes, wide curb lanes, combined bike/bus lanes, bike lanes next to motor vehicle parking, and wide paved shoulders.

Also included in this chapter is a summary of studies related to other bicycle-related measures along routes, including shoulder rumble strips (along roadway edgelines), traffic calming, bicycle boulevards, and bicycle paths (separated from the roadway).

Driver and cyclist reaction to the presence of various bicycle facilities are discussed where information is available.

This section involves a review of pertinent research studies on bicyclist safety from the U.S. and abroad. Some of the research results contained in this chapter were adapted or summarized from Clarke and Tracy (1995) (*132*) and also Hunter et al. (1999) (*133*).

Further research could be conducted on a city-wide basis on the effect of adding bike lanes along major corridors and the long-term effects on bicycle travel and crashes. Quantifying the effect of bike lanes, bike/bus lanes, and bike lanes next to parking on bike safety under a variety of traffic and roadway conditions would also be highly desirable. Further research is also needed on the safety effects of various types of rumble strips and traffic calming measures on bicyclist safety.

Exhibit 3-134: Resources examined to investigate the safety effect of bicycle facilities on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results not available.

DOCUMENT	DESCRIPTION	COMMENT
San Francisco's Department of Parking & Traffic.; and Alta Planning Design. San Francisco's Shared Lane Pavement Markings: Improving Bicycle Safety. Final Report, 2004	This study examines the effectiveness of shared-lane markings as used by both vehicles and cyclists. A before-and-after video analysis was used to evaluate the effectiveness of shared-lane markings. Examines the perception of drivers and cyclists using the share-lane.	Not added to synthesis.
(*68*) (Torbic, D. J., Elefteriadou, L., and El-Gindy, M., "Development of More Bicycle-Friendly Rumble Strip Configurations." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	Compared bicycle-friendliness of newly simulated rumble strip configurations at a test track in PA; both bicycles and motor vehicles tested the configurations	Added to synthesis.
(*134*) (Wilbur Smith Associates, "Bicycle Boulevard Design Tools and Guidelines." Berkeley, Calif., City of Berkeley Planning and Development Department, (2000))	Design manual developed by consultant for Berkeley, CA; general discussion of bicycle boulevards plus specific guidelines for implementation of a network of seven bicycle boulevards in the city of Berkeley	Limited qualitative information. Added to synthesis.
(*136*) (Hunter, W. W. and Stewart, J. R., "An Evaluation Of Bike Lanes Adjacent To Motor Vehicle Parking." Chapel Hill, Highway Safety Research Center, University of North Carolina, (1999))	Comparative study of conflicts and lateral positioning of bicycles at two FL sites with BLs and on-street parking; one site had a narrow traffic lane adjacent to the BL	Added to synthesis.
(*133*) (Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. F., and Pein, W. E., "A Comparative Analysis of Bicycle Lanes versus Wide Curb Lanes: Final Report." FHWA-RD-99-034, McLean, Va., Federal Highway Administration, (1999))	Comparative analysis of bicycle lanes versus wide curb lanes, sites in CA, FL, and TX, used conflicts as surrogate for safety	Added to synthesis.
(Hunter, W. W., Stewart, J. R., and Stutts, J. C., "A Study of Bicycle Lanes Versus Wide Curb Lanes." Transportation Research Record: Journal of the Transportation Research Board, No. 1667, Washington, D.C., Transportation Research Board, (1999) pp. 70-77.)	Same study as Hunter et al. 1999 (above)	Suggested by NCHRP 17-18(4). No new information. Not added to synthesis.
(Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. H., and Pein, W. E., "Bicycle Lanes Versus Wide Curb Lanes: Operational and Safety Findings and Countermeasure Recommendations." FHWA-RD-99-035, McLean, Va., Federal Highway Administration, (1999))	Same study as Hunter et al. 1999 (above)	No new information. Not added to synthesis.
(Garder, P., Leden, L., and Pulkkinen, U., "Measuring the Safety Effect of Raised Bicycle Crossings Using a New Research Methodology." Transportation Research Record 1636, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 64-70.)	A before/after methodology was applied to evaluate raised bike crossings at 44 intersections in Gothenburg, Sweden	Not added to synthesis. Used in the HSM bike intersection synthesis.
(*138*) (Harkey, D. L. and Stewart, J. R., "Evaluation of Shared-Use Facilities for Bicycles and Motor Vehicles." Transportation Research Record 1578, Washington, D.C., Transportation Research Board, National Research Council, (1997) pp. 111-118.)	Used observations of bicyclist and motor vehicle interactions in FL to evaluate the safety of shared-use facilities; wide curb lanes, bicycle lanes, and paved shoulders	Suggested by NCHRP 17-18(4). Added to synthesis.
(*139*) (Jensen, S. U., "Junctions and Cyclists." Barcelona, Spain, Proc. Velo City '97 - 10th International Bicycle Planning Conference, (1997))	Danish study of the effect of BLs on collision rates at signalized intersections and at priority intersections.	Limited qualitative information. Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D. and Stewart, R., "Bicycle and Motor Vehicle Operations on Wide Curb Lanes, Bicycle Lanes and Paved Shoulders." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 139-145.)	Analysis of bicyclists riding in midblock locations which had a bike lane, wide curb lane or shoulder. Behaviors and separation distances were recorded for motorists and bicyclists.	No quantitative information. Not added to synthesis.
(Florida DOT, "Florida Bicycle Facilities Planning and Design Manual, Final Draft." Tallahassee, Florida Department of Transportation, (1995))	Florida DOT design manual	Limited qualitative information. Not added to synthesis.
(*142*) (Garder, P., "Rumble Strips or Not Along Wide Shoulders Designated for Bicycle Traffic?" Transportation Research Record 1502, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 1-7.)	Discussion of the implementation of shoulder rumble strips along roadways with cycle traffic using the shoulder.	Limited qualitative information. Added to synthesis.
(Diepens and Okkema Traffic Consultants, "International Handbook for Cycle Network Design." The Netherlands, Delft University of Technology, (1995))	Handbook of bicycle treatment designs includes discussion of separate bike paths used in the Netherlands.	Limited qualitative information. Not added to synthesis.
(Herrstedt, L., Nielsen, M. A., Agustson, L., Krogsgaard, K. M. L., Jorgensen, E., and Jorgensen, N. O., "Safety of Cyclists in Urban Areas: Danish Experiences." Copenhagen, Denmark, Danish Road Directorate, (1994))	Evaluated various bike lane designs in an attempt to reduce potential conflicts between bus passengers and bikes.	Limited qualitative information. Not added to synthesis.
(Wilkinson, W. C., Clarke, A., Epperson, B., and Knoblauch, R., "The Effects of Bicycle Accommodations on Bicycle/Motor Vehicle Safety and Traffic Operations." FHWA-RD-92-069, Washington, D.C., Federal Highway Administration, (1994))	Conclusions are provided on bicycle planning and design based on the current state of the practice; recommendations are based on a literature review	Used as a reference (no original safety research conducted). Not added to synthesis.
(C.R.O.W., "Sign Up for the Bike: Design Manual for a Cycle-Friendly Infrastructure." C.R.O.W. Record 10, The Netherlands, Centre for Research and Contact Standardization in Civil and Traffic Engineering, (1994))	1994 Dutch design manual	Limited qualitative information. Not added to synthesis.
(Botma, H. and Mulder, W., "Required Widths of Paths, Lanes, Roads and Streets for Bicycle Traffic." The Netherlands, Grontmij Consulting Engineers, (1993))	Dutch study of bike lanes.	Limited qualitative information. Not added to synthesis.
(*147*) (Laursen, J. G., "Nordic Experience with the Safety of Bicycling." Denmark, Bicycle Federation of America, (1993))	Evaluated the safety benefits of bike lanes in Denmark	Limited qualitative information. Added to synthesis.
(*148*) (Ronkin, M. P., "Bike Lane or Shared Roadway?" Pro Bike News, Vol. 13, No. 3, Washington, D.C., Bicycle Federation of America, (1993) pp. 4-5.)	Analysis of bike lanes and shared lanes	Limited qualitative information. Added to synthesis.
(Egan, D., "A Bicycle and Bus Success Story." Montreal, Quebec, Canada, The Bicycle: Global Perspectives, (1992))	Study of shared bus and bike lanes in Toronto, Canada.	Limited qualitative information. Not added to synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Summarizes the safety effectiveness of various geometric features on pedestrian and bicycle safety, based on critical reviews of the literature	Used as a reference (no original safety research conducted). Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*150*) (Hass-Klau, C., Nold, I., Bocker, G., and Crampton, G., "Civilized Streets; A Guide to Traffic Calming." Brighton, United Kingdom, Environmental & Transport Planning, (1992))	Comprehensive discussion of traffic calming and cyclists.	Limited qualitative information. Added to synthesis.
(*151*) (Cyclists' Touring Club, "Cyclists and Traffic Calming." Godalming, United Kingdom, Cyclists' Touring Club; (1991)).	Advice for implementing traffic calming techniques without discouraging cyclists.	Limited qualitative information. Added to synthesis.
(*152*) (Tolley, R., "Calming Traffic in Residential Areas." Dyfed, Wales, United Kingdom, Brefi Press, (1990))	Study of traffic calming impacts on cyclists, volumes, delays, and speeds in Germany	Limited qualitative information. Added to synthesis.
(Harrison, J. H., Hall, R. D., and Harland, D. G., "Literature Review of Accident Analysis Methodologies and Cycle Facilities." Contractor Report 163, Berkshire, England, Transport and Road Research Laboratory, (1989))	Study of bus and bike shared lanes.	Limited qualitative information. Not added to synthesis.
(*154*) (Smith, R. L. and Walsh, T., "Safety Impacts of Bicycle Lanes." Transportation Research Record 1168, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 49-59.)	Evaluation of bicycle-motor vehicle crashes before and after BL installation.	Limited qualitative information. Added to synthesis.
(*155*) (Berchem, S. and Somerfeld, W. O., "Unique Roadway Design Reduces Bus-Bike Conflicts." TR News, No. 177, Washington, D.C., Transportation Research Board, National Research Council, (1985) pp. 2-3.)	Discussion of one design option for accommodating bus and bike traffic.	Limited qualitative information. Added to synthesis.
(*156*) (McHenry, S. R. and Wallace, M. J., "Evaluation of Wide Curb Lanes as Shared Lane Bicycle Facilities." Baltimore, Maryland State Highway Administration, (1985))	Studied wide curb lanes used by cyclists and motor vehicles.	Limited qualitative information. Added to synthesis.
(*157*) (City of Eugene, "18th Avenue Bike Lanes - One Year Report, Memorandum to City Council." Eugene, Oregon, (1980))	Evaluation of bike lanes in Eugene, Oregon	Limited qualitative information. Added to synthesis.
(*158*) (Lott, D. F. and Lott, D. Y., "Differential Effect of Bicycle Lanes on Ten Classes of Bicycle-Automobile Accidents." Transportation Research Record 605, Washington, D.C., Transportation Research Board, National Research Council, (1976) pp. 20-24.)	One of the earlier statistical analyses of the role that BLs played with regard to various types of bicycle-motor vehicle accidents	Limited qualitative information. Added to synthesis.
(Kroll, B. and Sommer, R., "Bicyclists Response to Urban Bikeways." Journal of the American Institute of Planners, Baltimore, American Institute of Planners, (1976) pp. 42-51.)	A survey of bike riders in the U.S. in 1976	Limited qualitative information. Not added to synthesis.

In general, the studies discussed below relate to bicycle treatments on urban roads, unless otherwise specified.

Discussion: Provide dedicated bicycle lanes

When bicycle lanes (BLs) were first becoming popular in the United States, assumptions were made about their implied safety benefits, although many people challenged these beliefs. Lott and Lott (1976) performed one of the earlier statistical analyses of the role that BLs played with regard to various types of bicycle-motor vehicle accidents (*158*). At that time, the City of Davis, CA, already had an extensive network of heavily used BLs, as well as many streets without them. The study included all functional types of the Davis street network. One phase of the Lott study compared the four-year accident experience revealed in police records for the roads that had BLs to those without BLs. Additionally, crash records in Davis were compared with those of Santa Barbara, CA, a comparable city that did not use BLs.

All of the accidents were categorized into a ten-class system, and the relative frequency with which each type of accident occurred in BL segments vs. non-BL segments was assessed. Three types of bicycle-motor vehicle accidents that seemed unaffected by BLs were used as a standard for evaluating the role of BLs in other categories of accidents; specifically (1) where a bicyclists failed to stop or yield at a controlled intersection, (2) where a motorist failed to stop or yield at a controlled intersection, and (3) where a motorist made an improper left-turn. The analysis found lower crash frequencies at locations with BLs in six classes of bicycle-motor vehicle accidents and higher frequencies in one class. The overall frequency of accident types that were considered to be affected by the presence or absence of BLs went down 51%. The frequency of all accident types combined decreased by 29% in area with BLs. Based on this evidence, Lott and Lott concluded that BLs do indeed offer positive safety benefits (*158*).

In Corvallis, Oregon, BLs were credited with decreasing bicycle-motor vehicle crashes by more than 50% (*148*). In Eugene, Oregon, a two-thirds reduction in bicycle-motor vehicle crashes was attributed to bike lanes (*157*).

In Madison, Wisconsin, BLs installed along a one-way arterial pair resulted in a statistically significant increase in the number of bicycle-motor vehicle crashes associated with turning movements during the first year after BL installation; but the number dropped sharply after the first year that the BLs had been in operation (*154*). The authors concluded that, overall, the BLs did not have an adverse effect on bike safety. In fact, the one roadway section where crashes increased during the first year was something of an anomaly in that it was installed on the left side of a one-way street.

Researchers in Denmark have evaluated the effectiveness of BLs as a bike safety measure. One study found a lower frequency of crashes resulting in injuries to cyclists on roadways that had a BL or bicycle path, compared with roadways that did not provide these facilities (Herrstedt et al., 1994 as cited by Hunter et al. (*133*)).

Another Danish study looked at the effect of BLs on collision rates at signalized intersections and at priority intersections (at priority intersections, traffic is controlled by signage rather than signals and one road has priority over the other). Results indicated that the implementation of BLs caused no change in the number of either bicycle-motor vehicle or overall crashes at signalized intersections. However, there was an increase in bicycle-motor vehicle crashes at priority intersections. The study also found a reduction in all crashes along the stretches of roadway between intersections (*139*).

Many of the above studies indicate a safety benefit after the installation of bicycle lanes. However, regression-to-the-mean may play a part in these studies; therefore the magnitude of safety effect is not known at this time.

Discussion: Width of bicycle lanes

Several State Departments of Transportation in the U.S., including New Jersey, North Carolina, and Oregon, suggest that bicycle lanes may generally be 4 to 6 ft (1.2 to 1.8 m) wide (*133*). Back in 1976, a survey of bike riders in the U.S. found that 85% of them considered BLs wider than 1.8 m to be adequate while only 41% felt that lanes less than 1.5 m wide were sufficient (Kroll et al., 1976 as cited by (*133*)).

The literature suggests that Dutch experts generally prefer wider BLs than their American counterparts. A 1994 Dutch design manual suggests lanes that are 2.0 m wide in order to accommodate cyclists who ride side-by-side (*133*). To allow for passing maneuvers within the bike lane, a 1993 Dutch study suggested providing lanes that are 2.5 m wide in locations where the one-hour peak volume is greater than 150 bicycles (Botma and Mulder, 1993 as cited by (*133*)).

Discussion: Bicyclist and motor vehicle driver reaction to bicycle lanes

In a nationwide survey of U.S. cyclists in 1976, 93% of the people using BLs felt that the roadway was safer with BLs than without those lanes (Kroll et al., 1976 as cited by (*133*)). However, Kroll et al. could offer no conclusive evidence that BLs improve the safety of people who use them.

A pavement marking stripe at the side of the road may be used to denote either a bicycle lane or a paved shoulder. In either case, research has shown that a stripe separating motor vehicle traffic from bicycles results in fewer erratic maneuvers on the part of motorists, more predictable riding movements by the cyclists, and higher levels of comfort for both bicyclists and motor vehicle drivers compared to a wide curb lane (*138*).

Discussion: Provide wide curb lanes (WCLs)

In cases where right-of-way limitations prevent installation of a full-width BL, one alternative is to design the curb lane wide enough to accommodate both bicyclists and motor vehicles and facilitate passing maneuvers. According to McHenry and Wallace, the ideal width for a wide curb lane (WCL) is between 4.0 and 4.6 m; this allows enough room for lane sharing but not so much that motorists double up in the lane at intersections (*156*). A study completed in 1994 suggested that WCLs are effective on roadways where the cycling population consists of mostly experienced riders (*131*). Harkey and Stewart found that motorists are much more likely to encroach into the adjacent lane of motor vehicle traffic when passing cyclists in a WCL than a delineated BL (*138*).

Currently, state and local officials appear more likely to install BLs than WCLs. This may be due to the influence of cyclists, who seem to prefer BLs. The Florida DOT, for example, states that because only 5% of bicyclists “feel comfortable” using WCLs, the WCL should be considered a last-resort treatment where BLs are not feasible (*133*).

A 1985 Maryland study suggested that curb lanes intended for shared use by bicyclists and motor vehicles need to be 15 to 15.5 ft (4.6 to 4.7 m) wide (*156*). McHenry et al. also found that a width of more than 12 ft (3.67 m) improves the interaction between bikes and motor vehicles in a shared lane, but the report cautioned that excessive width could be counterproductive. Wide curb lanes were also found to have a positive effect on both bicycle and motor vehicle flow patterns at midblock as well as allowing the greatest uniformity of tracking. McHenry et al. found that WCLs also caused the least amount of vehicle displacement (*156*), although this finding contradicts Harkey and Stewart’s conclusion, noted above, that motorists are more likely to encroach in the adjacent lane of motor vehicle traffic when passing cyclists in a WCL.

Overall, the safety effect of wide curb lanes has not been quantified, although the majority of research indicates that WCL improve safety, there are potential negative aspects to be considered prior to implementation.

Discussion: Bike lanes versus wide curb lanes

Harkey and Stewart did a study for the Florida DOT that focused on bicyclists riding in midblock locations that had a BL, a WCL (wide curb lane), or a paved shoulder (*138*):

- Bicyclists and motorists were separated by a distance of 1.8 m, with slight variation dependent upon the type of facility present (i.e., BL, WCL, or paved shoulder)
- In the case of BLs and paved shoulders, the distance between a cyclist and the roadway edge was greater (0.8 m) than on WCLs (0.4 m)
- When passing a bicyclist in a BL, motor vehicles shifted about 0.3 m laterally regardless of the BL width
- When passing a bicyclist using a WCL, motorists moved over to the left 0.4 m more than when passing someone using a BL or paved shoulder
- When passing a bicyclist using a WCL, motorists encroached 22.3% more into the adjacent lane to their left than when the cyclist was riding in a BL (8.9%) or a paved shoulder (3.4%)

A comparative analysis of bicycle lanes (BLs) versus wide curb lanes (WCLs) was conducted for the FHWA in 1999 (*133*). In the cities of Santa Barbara, CA, Gainesville, FL, and Austin, TX, videotapes were made of bicyclists approaching and riding through eight intersections that had BLs and eight others that had WCLs. At the BL locations, 2,700 cyclists were observed, while 1,900 cyclists were taped going through the WCL intersections. In addition, brief on-site interviews of 2,900 bicyclists were conducted; and an analysis was performed on crash data from bicycle-motor vehicle crashes (*133*).

Hunter et al. showed that 5.6% of all bicyclists on the videotapes were riding the wrong way, against traffic. One-third of the bicyclists at both types of facilities claimed to be experienced riders (*133*).

The videotapes of motor vehicle and bicycle traffic approaching the intersections (i.e., at midblock) revealed that a statistically significant higher percentage of vehicles passing bicyclists on the left encroached into the adjacent traffic lane at WCL locations (17%) than at BL sites (7%) (*133*), which agrees with findings from the Florida DOT study done in 1997 (*138*). Fortunately, the lane encroachments hardly ever caused conflict with motor vehicles using the other lane (*133*).

In cases where bicyclists were <u>not</u> being passed by motorists and the BL width was 1.6 m or less, the average bicyclist distance from the curb or gutter pan seam was less than for WCLs with the same amount of motor vehicle traffic volume. At locations where bicyclists were <u>not</u> being passed by motorists and the BL width was 1.6 m or greater, the average bicyclist distance from the curb was greater than for WCLs with the same amount of motor vehicle traffic volume (*133*). Comparable results were found in situations where cyclists <u>were</u> being passed by motorists; that is, the results were similar for both passing and no passing when the BL width is greater than 1.6 m. Test sections used in this study were from Santa Barbara, CA, Gainesville, FL, and Austin, TX, where a considerable amount of commuter bicycling occurred related to universities. Sites included a variety of traffic and roadway conditions.

The videotape evidence showed a total of 188 midblock conflicts. Broken down into percentages, 71% were bicycle/motor vehicle conflicts, 10% were bicycle/bicycle conflicts, and 19% were bicycle/pedestrian conflicts. Most of the conflicts between bikes happened in BLs, but there were more problems between bikes and pedestrians in WCLs (perhaps due to greater amount of cyclists riding on sidewalks in WCL locations) (*133*).

In their comment section, Hunter et al. suggest the findings contradict prevailing assumptions about the differences between WCLs and BLs. Many experts think that more experienced riders tend to use the WCLs and less proficient cyclists opt for BLs or sidewalks; survey results in this study found no difference in cyclist experience according to type of facility. Similarly, the common belief that riding the wrong way is more common among BL users was called to question by results of this study, which found a higher proportion of people going against traffic at the WCL sites. Of course, this might be due to the fact that WCLs are often found on higher volume roadways, where cyclists seek what they think is the safest route possible. Data from both BL and WCL locations suggest the need for educating cyclists about the safest way to make both left and right turns at intersections (*133*).

Hunter et al. state that (*133*):

"The overall conclusion of this research is that both BL and WCL facilities can and should be used to improve riding conditions for bicyclists, and this should be viewed as a positive finding for the bicycling community. The identified differences in operations and conflicts were related to the specific destination patterns of bicyclists riding through the intersection areas studied."

The authors suggest the use of BLs "…where there is adequate width, in that BLs are more likely to increase the amount of bicycling than WCLs" (*133*).

Another Danish study evaluated the safety benefits of bike lanes determined that, "for some reason" BLs were just as effective as separate bike paths ("cycle tracks"), although bicyclists claimed to feel less safe on BLs (Hansen, 1983 as cited by (*147*)). Even when the lanes were barely wide enough for a bicycle (0.5 m or 19.7 inches), Laursen found that a BL reduced bicyclist crash risk by up to one-third, with lanes that were a little wider (0.6 m or 2 ft) reducing bicyclist crash risk 70 to 80%.

Discussion: Combined bus and bicycle lanes; bus and bicycle interaction

In Toronto, the installation of a lane shared by buses and bicycles lowered crash rates. Bicycle traffic increased after the lane was added, and over 75% of the cyclists surveyed claimed to feel safer riding in this newly provided space, compared to riding on a street with standard lanes (Egan, 1992 as cited in (*133*)).

Recognizing the potential danger of conflicts between the two modes of transportation at crossing points, one design option designates a bike lane to the right of the through traffic lanes but to the left of the bus and right-turn lane. This design permits the continuous flow of bicycle traffic while accommodating the need for bus stops (*155*).

Addressing the high crash rate for various road users in bus stop areas, Danish researchers have tried to reduce potential conflicts between bus passengers and bikes by using unique pavement markings to highlight the conflict area at bus stops and divert cyclists away from passengers disembarking from the stopped buses. The designs evaluated in a 1994 study by Herrstedt included (as cited in (*133*)):

- Combining a pedestrian crossing with profiled pavement markings;
- Placing a profiled marking on the offside of the bike path; and
- Painting a pattern that included a visual brake.

As it turned out, none of these designs increased the percentage of bicyclists who yielded to bus passengers crossing the bike path; but all three designs encouraged cyclists to slow down when a bus was present at the stop. With the special pavement markings in place, cyclists reacted sooner when they saw a bus at the stop, which reduced the distance between point of initial reaction and the closest potential conflict area. The painted pattern actually lowered the number of serious conflicts that occurred (Herrstedt et al., 1994 as cited in (*133*)). No details regarding road type, volumes, speeds, or study methodology were reported.

Discussion: Bike lanes adjacent to motor vehicle parking

Where on-street parking exists, retrofitting the roadway to accommodate a bike lane may result in a traffic lane next to the BL that is somewhat narrower than standard. A study in Florida compared roadways in Ft. Lauderdale (Route AIA) and Hollywood (Hollywood Blvd) that have BLs adjacent to motor vehicle parallel parking (*136*). Both BLs are about five feet wide, but restriping to add the BL in Ft. Lauderdale reduced the width of the traffic lane next to it to 10.5 ft, whereas the Hollywood location has a standard 12-ft lane beside the BL.

Hunter et al. gathered videotape data on conflicts between bicyclists and motorists, pedestrians, and other bicyclists, with a conflict being defined as a sudden change in speed or direction of travel to avoid a collision. As it turned out, conflicts were rare, minor, and occurred mostly in the BLs. Six of the eight conflicts (75%) observed in Ft. Lauderdale were related to parking maneuvers, not surprising given the frequent turnover in parking spaces so close to the beach. At the Hollywood site, four of the five conflicts (80%) involved side street traffic rather than parking maneuvers (*136*).

Lateral positioning of the bicycles was also evaluated in order to identify issues stemming from the narrow traffic lane next to the Ft. Lauderdale BL. At both locations, however, it was found that cyclists favored the center of the BL when parked cars were present. Cyclists were also a little more likely to ride farther away from traffic if the parked vehicles were closer to the curb, but the position of a parked vehicle did not affect the tendency at both locations to ride farther away from traffic when being passed (*136*).

Average separation between bicyclists and passing vehicles was 5.77 ft on Route A1A (i.e., with the narrow travel lane) and 7.52 ft on Hollywood Boulevard (i.e., with the 12 ft motor vehicle lane) a difference of approximately 1.8 ft (which was statistically significant at the .001 level). The authors felt that, despite busier conditions, a narrower BL, and a narrower adjacent traffic lane, the cyclists in Ft. Lauderdale adjusted easily to the situation. The bicycles were never spaced less than an acceptable three feet from ongoing traffic. Overall, the researchers concluded that narrowing the traffic lane to 10.5 ft to accommodate a BL next to on-street parallel parking had succeeded (*136*).

Discussion: Paved highway shoulders used by cyclists, and shoulder rumble strips

According to Harkey and Stewart, Khan and Bacchus (1995) found that the expected number of bicycle-motor vehicle crashes is greatly reduced when cyclists ride on paved highway shoulders instead of sharing a lane with motorists. Paved shoulders affect the interaction between bicycles and motor vehicles basically the same as BLs in that the strip which separates the two modes of traffic promotes lowered risk for both (*138*).

Additional evaluations are needed to confirm the safety effect of cyclists using a paved shoulder on various road types with different volumes and operational characteristics.

There is a potential danger to cyclists riding on a paved shoulder if inattentive or sleepy motorists drift off the road. A shoulder rumble strip is one countermeasure used to address this problem, although the most effective design has not yet been determined (*142*). At least 1.5m in width is necessary to allow enough space for both a rumble strip and bicyclists on highways with speeds of less than 100 km/h (Khan and Bacchus, 1995 as cited in (*133*)).

Since bicyclists are usually prohibited from riding alongside freeways, the use of rumble strips on these roadways is not typically a problem for the cycling population. However, with the increasing use of rumble strips on other types of roads, the authors of one study chose to evaluate newer designs that would be safer and more comfortable for cyclists while still effective in preventing run-off-road accidents by alerting inattentive or sleepy motorists (*68*). New rumble strip models were simulated, installed, and evaluated on a test track in Pennsylvania. The models were subjected to testing with both bicycles and motor vehicles. Results led to a new rumble strip configuration for use along high-speed non-freeway facilities and another for use on lower-speed roadways (*68*):

1. 127 mm wide, 178 mm edge to edge between cuts, 10 mm deep for operating speed of 55 mph (88 km/h)
2. 127 mm wide, 178 mm edge to edge between cuts, 6.3 mm deep for operating speed of 45 mph (72 km/h)

Torbic et al. provide detailed discussion on the evaluation process (*68*). Section 3.2.4 contains further discussion of shoulder rumble strips.

Discussion: Traffic calming

German planners have implemented a number of traffic-calming techniques that have affected bicyclist as well as motor and pedestrian safety. In some urban areas, arterials with a maximum speed of 50 km/h (33 mph) have been fitted with synchronized traffic signals, bike lanes, marked crosswalks, wide sidewalks, and medians. On collector roads having a maximum speed of 30 km/h (18 mph), designers have installed narrow lanes, bike lanes, speed tables, and wider sidewalks that force motorists to obey the speed limit. Movement along residential streets has been slowed down through the use of managed parking, chicanes, reclaimed play areas, speed humps, and road closures.

In Germany and other countries, the use of traffic-calming techniques like these has increased bicycling, walking, and other kinds of street activity. In some cases, both fatal and injury crashes among all road users have been lowered as much as 60%. One major study showed that even though traffic volume did not change and speeds were reduced, motorists had only faced an average 33 second delay (*152*). Traffic calming has proven popular with citizens and beneficial to the environment. Tolley says that, in Germany, savings in accident costs alone will counteract the expense of installing traffic calming.

Probably the most comprehensive discussion on this topic is “Civilized Streets: A Guide to Traffic Calming” (*150*). Many locations in Germany, the United Kingdom, the Netherlands, and Denmark have developed standards and guidelines for traffic calming. The Cyclists Touring Club (1991) has offered advice for implementing these techniques in the United Kingdom without discouraging bicycling (*151*).

Traffic calming on roadway segments is also discussed in Section 3.2.6.

Discussion: Bicycle boulevards

In an effort to make itself more bicycle-friendly, the City of Berkeley, CA, has designed a network of seven bicycle boulevards. The city's design consultant describes a bicycle boulevard as "a roadway that has been modified as needed to enhance bicyclists' safety and convenience" (*134*). This type of facility can help solve the problem of providing safe, efficient bikeways in urban areas with limited street space. Collaborating with neighborhood residents and cyclists, Wilbur Smith Associates created a toolbox of site-specific strategies for developing the seven bicycle boulevards within the city of Berkeley.

A bicycle boulevard includes a number of unique features. Although a BL can be provided if necessary, a bicycle boulevard is usually designed as a shared facility where motor vehicle traffic is low in volume and limited to local traffic. Ambiance, traffic control, and intersection features make it clear to both cyclists and motorists that the boulevard is intended to give priority to bicyclists. Overall, the purpose of a bicycle boulevard is to provide a place where almost anyone would feel safe riding and to provide a network of roadways on which cyclists can move efficiently through the city (*134*).

A bicycle boulevard shares many of the safety benefits found with other forms of traffic calming. Lower motor vehicle traffic volumes and speeds, as well as the priority given to cyclists at crossings, combine to reduce potential conflicts between these two modes of transportation and the severity of such conflicts if they do occur. However, these assumed benefits would be hard to prove empirically since the roadways selected for conversion to bicycle boulevards tend to be low-accident areas anyway (*134*).

A network of bicycle boulevards provides riders with a more continuous, direct route with fewer stops and delays. Use of the boulevards can make bicyclists more visible in the community, which in turn makes them feel safer and motorists more aware of their presence. In addition, the reduction in motor vehicle volume, speed, and noise, plus easier street crossings along bicycle boulevards, can have obvious benefits for pedestrians and for the local neighborhoods in which these facilities are located. The report contained no formal evaluation on the effectiveness of bicycle boulevards on bike crashes (*134*).

Discussion: Bicycle paths

Dutch designers suggest installation of a separate bicycle path where motor vehicle speeds are greater than 50 km/h or traffic volumes are higher than 1,200 veh/hr. A space at least 1.8 m wide should be allotted for one-way bike paths, while 2.8 m is necessary for two-way paths (Diepens and Okkema, 1995 as cited in (*133*)). American cyclists surveyed in 1976 by Kroll and Sommer felt that bike paths were safer than bike lanes and considered 2.8 m to be a good width for a bike path (Kroll and Sommer, 1976, as cited in (*133*)).

Although there is some evidence that separate bike paths can provide a relatively safe facility along a roadway segment, particularly in a rural or outlying area, the crossings of the paths at intersections result in an overall higher rate of bicycle crashes along most routes, particularly in urban and suburban areas.

Summary

The majority of research on bike lanes suggests that the addition of well-planned and well-designed bike lanes can improve bicyclist safety compared to wide curb lanes. Bike lanes should be a minimum of 5 ft wide and properly signed and marked. Bike lanes have also been found to result in more consistent lateral placement between bicyclists and passing motorists, and most bicyclists prefer riding in bike lanes, compared to riding in travel lanes without bike lanes. Wide curb lanes (greater than 15 ft) provide for safer movements of bicyclists than lanes of 12 feet or less. Providing paved shoulders provides a safer riding environment for bicyclists, compared to travel lanes without a paved shoulder.

The question of whether to install bike lanes next to motor-vehicle parking is somewhat controversial. However, there is evidence that it can be done successfully for a 5-foot bike lane. A combined bus/bike lane has shown to be a reasonable measure to help promote safe interaction between bicyclists and buses along bus routes if proper pavement marking is used.

There has also been controversy on the use of edgeline rumble strips, in terms of how it affects bicyclists on paved shoulders. While some rumble strip designs create a problem for bicyclists, some newer rumble strip designs have been found to reduce the likelihood of a motor vehicle running off the road (and thus less likely to strike a bicyclist), while also being less of an obstruction for bicyclists who ride on the shoulder.

Separated bike paths are discussed briefly in this chapter. There is evidence that although they can provide a relatively safe facility along a route, particularly in a rural or outlying area, the crossings of the paths at intersections result in an overall higher rate of bicycle crashes along most routes, particularly in urban and suburban areas. Bike boulevards (i.e., bike-friendly streets with low vehicle speeds where bike have priority over motor vehicles) have been used in some cities. Bike boulevards have the potential for providing a safer bicyclist environment, although no quantitative studies were found which has conducted such an analysis. Certain types of traffic calming measures can reduce vehicle speeds and create a safer environment for bicycling.

3.3.5. School Routes and School Zones [Future Edition]

In future editions of the HSM, this section may provide discussion of the safety effects of various conditions related to elementary and high school transportation, including but not limited to: bus stops, use of the “walking bus”, special signage, the presence of crossing guards, traffic calming devices, school zone enforcement, and presence of sidewalks. Potential resources are listed in Exhibit 3-135.

Exhibit 3-135: Potential resources on safety of school routes and school zones

DOCUMENT
(Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Collisions Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))

(Weiss, A. and Schifer, J. L., "Assessment of Variable Speed Limit Implementation Issues." NCHRP 3-59, Washington, D.C., Transportation Research Board, National Research Council, (2001))
(Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))
(Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))

3.3.6. Weather Issues [Future Edition]

The safety implications of weather issues on pedestrians and bicyclists may be discussed in this section in future editions of the HSM. Discussion of snow/slush/ice control may be of interest on sidewalks, crosswalks, and paths. This section will add to the discussion of Section 3.4. Potential resources are listed in Exhibit 3-136.

Exhibit 3-136: Potential resources on weather issues and pedestrian and bicycle safety on segments

DOCUMENT
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))

3.4. Safety Effects of Other Roadway Segment Elements

Other roadway segment elements include illumination, access points, transit stops, weather, pavement materials, and wild animals. The safety effect of characteristics contained in these elements will be addressed in the following sections.

3.4.1. Highway Illumination

Artificial illumination is often provided on road segments in urban and suburban areas, and also at locations in rural settings where drivers may need to make a decision.

This section presents evidence regarding the safety effect of public lighting on roadway segments. This refers to the introduction of lighting on highways that were not previously illuminated.

The reader may wish to review Section 2.4, Human Factors in Road Safety, for a discussion on conspicuity and lighting.

A meta-analysis of 37 evaluation studies containing 142 estimates of effect has been reported by Elvik (1995) (*160*). This analysis serves as the main source of evidence used in this section. The analysis has been updated by adding the studies of Griffith (1994) (*161*), Preston (1999) (*162*) and Wanvik (2004), the latter subject to a re-analysis by Elvik (2004) (*8*).This brings the total number of studies to 40 and the total number of estimates of effect to 152. This includes estimates of the effects of illumination both on highway segments and at intersections. Most studies do not specify whether the estimates of effect refer to highway segments only or include intersections as well. It was therefore decided to make use of all available evidence. State-of-the-art techniques of meta-analysis have been applied to summarize evidence from these studies.

Studies have been classified in three groups according to study quality. Studies rated as high quality include studies using both an internal and external comparison group (the distinction between external and internal comparison is explained below) and matched case-control studies. Studies rated as medium quality include studies that provide data on traffic volumes in addition to accident data, and studies using an external comparison group only. Studies rated as low quality include studies that use only an internal comparison group and simple (as opposed to matched) case-control studies. Most studies, representing 74% of the estimates of effect, have been rated as low quality. Standard errors have been adjusted by a factor of 1.2 in high quality studies (all study designs), 2 in medium quality before-and-after studies, and 3 in low quality before-and-after studies. In case-control or cross-section studies, standard errors were adjusted by a factor of 3 in medium quality studies and a factor of 5 in low quality studies.

An internal comparison group refers to the use of daytime accidents as a comparison group when estimating the effect on lighting. As an example, suppose there were 80 accidents in daytime and 55 in darkness at a location before lighting was installed. Further, suppose the number of accidents in daytime increased to 84 and the number of accidents in darkness declined to 39 after lighting was installed. The effect would then be estimated to be: (39/55)/(84/80) = 0.675.

This study design does not control for two potential confounding factors: (1) Long-term trends in the proportion of accidents occurring in darkness, and (2) Regression-to-the-mean, in particular with respect to an abnormally high proportion of accidents in darkness. To some extent, both these confounding factors can be controlled for by using an external comparison group, i.e. highway sections where lighting has not been installed. Suppose, for example, that for comparison roadway segments where lighting was not installed, the following numbers were observed during before and after periods matching the location above where lighting was installed: daytime before = 112; daytime after = 119; darkness before = 58; darkness after = 54. Then, in the comparison group, the odds ratio would be: (54/58)/(119/112) = 0.876. The adjusted estimate of effect (ratio of odds ratios) would be: 0.675/0.876 = 0.771.

Exhibit 3-137: Resources examined to investigate the safety effect of illumination on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., R. Srinivasan, J. Baek, B. Persaud, C. Lyon, F.M. Council, K. Eccles, N. Lefler, F. Gross, E. Hauer, J. Bonneson, "Crash Reduction Factors for Traffic Engineering and ITS Improvements", NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including providing highway lighting along all roadway settings	Added to synthesis. Includes AMF.
(Campbell, B. J, Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	An overview of research studies on pedestrian safety, and this particular report is an update of two earlier reports	No new information. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Collisions Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies aimed at reducing crashes involving older drivers.	No AMFs. Not added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Synthesis of a variety of reports on the reduction of crashes on horizontal curves	No AMFs. Not added to synthesis.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of many treatments, including illumination. Reanalysis of Wanvik (2004).	Added to synthesis.
(Wanvik, P.O., "En undersøkelse av sammenhengen mellom vegbelysning og trafikkulykker på 35 strekninger i Region sør", Statens vegvesen, Region sør, Drammen (2004))	Added to Elvik and Vaa's metanalysis.	Added to synthesis.
(Sullivan, J. M. and Flannagan, M. J., "The Role of Ambient Light Level in Fatal Crashes: Inferences from Daylight Saving Time Transitions." Accident Analysis and Prevention, Vol. 34, No. 4, Oxford, N.Y., Pergamon Press, (2002) pp. 487-498.)	Three specific countermeasures were tested against each other in a single scenario that would be reasonable match to each	Does not address the effects of lighting. Not added to synthesis.
Yi, Ping.; John, L. J.; Dissanayake, S.; and Zang, Y. Impact of highway Illumination on Traffic Fatality in Various Roadway and Environmental Conditions. Transportation Research Record, TRB, National Research Council, Washington, D.C., 2002	This study compares collisions in lighted and unlighted conditions by evaluating the interaction of roadway, traffic, weather conditions and age of driver at the time of collisions. The two-way ANOVA technique was used to evaluate the interactions.	No safety effects reported. Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Compilation of data including safety, geometric, and traffic with a broad range of suggested countermeasures	Too few details to be included in meta-analysis.
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))	Review of existing literature and data sets to determine the relationship between speed and resulting pedestrian injury	No AMFs. Not added to synthesis.
(*162*) (Preston, H. and Schoenecker, T., "Safety Impacts of Street Lighting at Rural Intersections." 1999, St. Paul, Minnesota Department of Transportation, (1999))	Conducted both a cross-sectional study (3,400 intersections) and a before-and-after analysis (12 intersections) of the effect of street lighting on rural intersection safety	Suggested by 17-18(4). Added to synthesis.
(*160*) (Elvik, R., "Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure." Transportation Research Record 1485, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 112-123.)	Meta-analysis of 37 studies on the safety effect of illumination; illumination of various types of roadway segments included	Suggested by 17-18(4). Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*161*) (Griffith, M. S., "Comparison of the Safety of Lighting Options on Urban Freeways." Public Roads, Vol. 58, No. 2, McLean, Va., Federal Highway Administration, (1994) pp. 8-15.)	Used crash data to compare the safety of continuously lighted urban freeways and urban freeways with interchange lighting only	Suggested by 17-18(4). Added to synthesis.
(Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume I - Access Control." FHWA-RD-91-044, Washington, D.C., Federal Highway Administration, (1992))	A literature review and discussion on the basic findings which relate access control to the safety of a highway facility	Not relevant to this section. Not added to synthesis.
(Keck, M. E., "The Relationship of Fixed and Vehicular Lighting to Accidents." FHWA-SA-91-019, McLean, Va., Federal Highway Administration, (1991))	Synthesis of research results covering a period from 1979 to 1988	Refers to Richards (1981) included in Elvik (1995). Not added to synthesis.
(Box, P. C., "Major Road Accident Reduction by Illumination." Transportation Research Record 1247, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 32-38.)	Before and after study on the effect on crashes of illumination at one site, 2.8 km in length	Suggested by 17-18(4). Used in Elvik (1995) meta-analysis.
(Mueller, E. A. and Rankin, W. W., "Pedestrians." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 8, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	A synthesis of research findings on the safety effects of specific traffic control measures and roadway elements	Reviewed and included in Elvik (1995). Not added to synthesis.
(Cleveland, D. E., "Illumination." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 3, Washington, D.C., Automotive Safety Foundation, (1969))	A synthesis of research findings on the safety effects of special design and control features	Reviewed and included in Elvik (1995). Not added to synthesis.

Exhibit 3-138 shows summary estimates of the effects of lighting on accidents. Effects are stated as odds ratios. Uncertainty in summary estimates of effect is stated as adjusted standard error. All estimates of effect refer to accidents in darkness only.

Two sets of summary estimates of effect are presented in Exhibit 3-138. The first is based on conventional meta-analysis. The second set has been generated from coefficients estimated in meta-regression analysis. In theory, the meta-regression estimates are superior to the conventional summary estimates, since they control for more confounding factors or imbalance in the distribution of estimates across moderator variables (a moderator variable is any variable that influences the size of the effect of a measure on accidents).

Only estimates that specify accident severity have been used. Estimates referring to “all” accidents, which is usually a mixture of fatal, injury and property-damage-only accidents have been discarded. The number of estimates underlying each summary estimate is stated in parentheses.

All summary estimates of effect, both those based on the conventional meta-analysis and those based on meta-regression, indicate that illumination reduces the number of accidents. There is a very systematic pattern in summary estimates of effect: the largest effect is found for fatal accidents, the smallest effect is found for property damage only accidents. There is little variation in effect between various types of traffic environment (e.g., rural, urban). This applies both to the conventional summary estimates and to the summary estimates based on meta-regression. It is therefore clear that illumination reduces the number of accidents in darkness, in particular fatal accidents.

Some of the conventional summary estimates are based on very few estimates of effect. These summary estimates have large standard errors. In subsets that contain few estimates of effect, the standard errors are smaller for the meta-regression summary estimates than for the conventional summary estimates. The meta-regression summary estimates indicate larger effects on accidents in nearly all cases than the conventional summary estimates. The reasons for this are not clear. It is a bit surprising, since the effects attributed to road safety measures often tend to get smaller the more confounding or contextual variables a study controls for. In this case, the opposite pattern is found (Exhibit 3-138).

Exhibit 3-138: Summary estimates of the effects on accidents of public lighting

		Summary estimate of effect and standard error	
Traffic environment	**Accident severity**	**Summary estimate**	**Standard error**
Summary estimates based on conventional meta-analysis			
All types of highway	All types, Fatal (18)	0.313	0.361
	All types, Injury (85)	0.717	0.056
	All types, PDO (19)	0.825	0.072
Rural highways	All types, Fatal (2)	0.265	0.720
	All types, Injury (19)	0.802	0.124
	All types, PDO (1)	0.696	0.426
Urban highways	All types, Fatal (13)	0.365	0.515
	All types, Injury (46)	0.685	0.073
	All types, PDO (16)	0.840	0.075
Freeways	All types, Fatal (3)	0.274	0.712
	All types, Injury (20)	0.728	0.121
	All types, PDO (2)	0.678	0.256
Summary estimates based on meta-regression analysis			
All types of highway	All types, Fatal	0.261	0.285
	All types, Injury	0.577	0.208
	All types, PDO	0.590	0.217
Rural highways	All types, Fatal	0.269	0.273
	All types, Injury	0.594	0.192
	All types, PDO	0.607	0.202

Urban highways	All types, Fatal	0.260	0.257
Summary estimates based on meta-regression analysis			
	All types, Injury	0.576	0.169
	All types, PDO	0.589	0.180
Freeways	All types, Fatal	0.253	0.269
	All types, Injury	0.559	0.187
	All types, PDO	0.572	0.197

NOTE: The number of estimates underlying each summary estimate is stated in parentheses.

The meta-regression analysis shows that the differences in effects of illumination between different types of highways are minor and far from statistically significant. Hence, differentiating estimates of effect with respect to the type of highway does not seem to be justified. Therefore the use of the same values for the safety effects of illumination on all types of highway seems reasonable.

Harkey et al. (2008) conducted an additional meta-analysis and, in conjunction with the findings of an expert panel, developed AMF values for roadway segment lighting (*168*). The meta-analysis utilized data from 38 previous studies to determine results according to crash severity and time of day. The expert panel believed that the AMFs were best presented in a combined fashion for all injury accidents. The resulting AMFs are presented in Exhibit 3-139.

Exhibit 3-139*: Summary estimates of the effects on accidents of public lighting by severity and time of day (168)*

Nighttime Crashes	**AMF**
Total Crashes	0.80
All Injury Crashes	0.77
All Crashes	**AMF**
Total Crashes	0.94
All Injury Crashes	0.94

3.4.2. Increase Pavement Friction

Increasing the road surface pavement friction is often provided along roadway segments in response to both a high proportion of wet-road accidents and low friction numbers (*168*). Treatments involving a 1.5 in resurfacing or a 0.5 in microsurfacing using non-carbonate aggregates can be used to improve the pavement skid resistance. This section discusses the safety effect of increasing the pavement friction on roadway segments.

Exhibit 3-140: Resources examined to investigate the safety effect of increased pavement friction on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(Harkey, D.L., R. Srinivasan, J. Baek, B. Persaud, C. Lyon, F.M. Council, K. Eccles, N. Lefler, F. Gross, E. Hauer, J. Bonneson, "Crash Reduction Factors for Traffic Engineering and ITS Improvements", NCHRP Project 17-25 Final Report, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2008))	Researched and/or developed AMF values for a number of roadway segment treatments including increasing pavement friction.	Added new AMFs.

Treatment: Increase pavement friction

Rural two-lane roads, rural divided multilane highways, urban arterials, and suburban arterials

Harkey et al. (2008) conducted a reanalysis of data provided from a previous study from the NYDOT involving an examination of the safety impacts of improving pavement skid resistance *(168)*. An empirical Bayes before-after analysis was conducted on the data which included 36.3 miles (118 segments) and 1242.4 miles (2108 segments) of treated and untreated locations, respectively. Sites that were treated exhibited both a high proportion of wet-road accidents and low friction numbers (i.e., below the Programmatic Design Target Friction Number, FN40R of 32). The results generally showed statistically significant reductions in crashes for all roadway and crash types. Intuitive thinking was confirmed, that the greatest benefit was found on wet weather crashes. The notable exception to these general trends was found on two-lane rural roads where no significant change was found. The resulting AMFs are found in Exhibit 3-141.

Exhibit 3-141*: AMFs on increased pavement friction for roadway segments (168)*

Accident type Severity	AMF	Std. Error
All types All severities	**0.76**	**0.03**
Wet-road All severities	**0.43**	**0.03**
Rear-end All severities	**0.83**	**0.05**
Rear-end wet-road All severities	**0.58**	**0.07**
Single vehicle All severities	**0.70**	**0.05**

3.4.3. Access Points

Within the context of the HSM, a roadway segment is defined as the road between two major intersections and may include minor intersections and driveways. As Hauer points out, the prevailing belief is that traffic flow and access are the two main determinants of the safety of a road (*163*). Control of access spacing and density is critical because ensuring that intersections/driveways are not in the areas of influence of other intersections/driveways essentially separates conflict points and makes it easier for drivers to react and respond to traffic conflicts.

This section addresses the safety effect of access density or number of access points per unit length of road on roadway segments. Consideration is given to the road class, function of the road, and traffic control method.

In future editions of the HSM, this section may contain specific driveway-related issues, such as access density, conflict points, and limiting entrances to right in-right out; sight triangles and obstructions to view; alignment of the corridor and time to view oncoming traffic; the number of lanes to cross, median treatment, etc. This section would not subtract or repeat driveway knowledge from related sections, such as Section 6.5.

The safety impact of providing turn lanes for midblock access points may also be included here, and may include discussion of both right and left-turn lanes provided for private driveways. Some elements that may be addressed are: high volumes, signage, sight lines, acceleration/deceleration lanes, traffic control (unsignalized), pavement markings, curbs, medians, pedestrian, and bicycle-related safety effects when installing the midblock turn lanes.

The reader may wish to review related material presented in Chapter 4 and Chapter 7.

Exhibit 3-142: Resources examined to investigate the safety effect of access points and roadway segments on road networks

DOCUMENT	DESCRIPTION	COMMENT
(Fitzpatrick, K., E.S. Park, W.H. Schneider, "Potential Driveway Density Accident Modification Factors for Rural Highways Using Texas Data", Transportation Research Board 87th Annual Meeting, Washington D.C., (2008))	Negative binomial regression analysis of two- and four-lane rural roads in Texas. Results of analysis were used to create models representing the effect of driveway density on crashes for roadway segments.	Added to synthesis. AMFs quantify safety effects of access point density.
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis. t and s values calculated using available information.
(*163*) (Hauer, E., "Access and Safety." (2001))	Report is a critical review of previous research studies that investigated the safety effects of intersection spacing and driveway density	Added to synthesis. AMFs to quantify safety effects of changing intersection and driveway densities found.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways through a review of previous studies.	Not added to synthesis. Only generic information on access management found.

DOCUMENT	DESCRIPTION	COMMENT
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000)).	Identified the relationship between access point density and safety. Access point density is accounted for by the density of driveways on a roadway segment. For the base model, 3 driveways per kilometer (5 driveways per mile) was the nominal condition. This can be modified with a crash reduction factor that combines driveway density and ADT. As the density increases over five driveways per mile, the crash risk increases. For segments with less than the five driveways per mile, the crash risk decreases.	Not added to synthesis. AMF for driveway density is based on research by Muskaug (1985) which has already been incorporated into synthesis as part of meta-analysis by Elvik and Vaa (2004).
(*164*) (Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999))	Provides the results of numerous research studies on the safety impacts of various access management techniques	Added to synthesis. Information about changes in accident rates resulting from changes in signalized and unsignalized access-point densities added.
(Papayannoulis, V., Gluck, J. S., Feeney, K., and Levinson H.S., "Access Spacing and Traffic Safety." Dallas, Tex., Transportation Research Board Urban Street Symposium, (1999))	Reviews studies that relate safety to access spacing. Conducted analyses of crash data and access spacing; data from eight states; urban and rural analyzed separately	Not added to synthesis. Results from this study already incorporated into synthesis as part of review from a more recent reference by same authors (Gluck et al., 1999)
Gattis, L. J.; and Blackwell, Mack. Comparison of Delay and Accidents on Three Roadway Access Designs in a Small City. National Conference on Access Management, 1999.	This study examined safety issues with respect to traffic delay times and access density. The study didn't estimate any safety effect for access density or travel delay.	Not added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Synopsis of a number of safety topics and only includes generic (anecdotal) statements about there being higher accident rates associated with higher access point densities. These trends have already been well established and discussed at length in this synthesis.	Not added to synthesis. No quantified evidence was found.
(*38*) (Gattis, J. L., "Comparison of Delay and Accidents on Three Roadway Access Designs in a Small City." Vail, Colo., Transportation Research Board 2nd National Conference, (1996) pp. 269-275.)	Compared crash rates of three corridors with various types of access management.	Added to synthesis. Quantitative information on types of access control found. Insufficient data to determine t and s values.
(Lall, B. K., Eghtedari, A., Simons, T., Taylor, P., and Reynolds, T., "Analysis of Traffic Accidents within the Functional Area of Intersections and Driveways." TRANS-1-95, Portland, Ore., Portland State University, Department of Civil Engineering, (1995))	Analyzed 29 miles of Oregon Coast Highway; considered effect of driveways within the functional area of both urban and rural intersections. Limitations of the study with regards to the sample size (which affected the standard error values) and potential influence of confounding factors which have not been accounted for.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(McGuirk, W. W. and Satterly, G. T., "Evaluation of Factors Influencing Driveway Accidents." Transportation Research Record 601, Washington, D.C., Transportation Research Board, National Research Council, (1976) pp. 66-72.)	Study investigated the factors that influence driveway accidents through the development of various regression equations.	Not added to synthesis. Regression equations developed cannot be used to determine t and s values. Other anecdotal findings have already been incorporated in synthesis as part of review of other references.
(Box, P. C., "Driveways." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 5, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Chapter discusses the relationship between accidents and driveways / access management.	Not added to synthesis. Insufficient data to determine t and s values. Majority of anecdotal information or discussions have already been incorporated from review of more recent references.

According to Hauer, considerations for intersection spacing are traditionally governed by considerations of delay, signal coordination, signal timing and a myriad of other operational elements. Hauer further noted that as the number of access points (i.e., signalized/unsignalized intersections and driveways) increases, so does the number of accidents (*163*). This finding is not new and many studies in the past forty years have shown that accident rates generally rise with the increased frequency of driveways and intersections. The basic premise underlying this finding is that access points introduce conflicts and friction into the traffic stream (*164*).

For example, suppose that one driveway causes (A) accidents/year. A one mile segment with (B) driveways will then have:

$$Y = A \times B \text{ accidents/year} \quad (1)$$

And a driveway spacing of:

$$X = 1/B \text{ miles} \quad (2)$$

Substituting for B into (1):

$$Y = A/X$$

This shows that as driveway spacing (X) increases, the expected frequency of accidents (Y) diminishes. It follows by logic from the premise that each driveway causes some fixed number of accidents. Thus, the predominant issue is not how (Y) changes as a function of driveway density or spacing but how many accidents each driveway adds. The number of accidents caused by each driveway (A) would be a function of a number of variables including the traffic volume on the main road, the number of lanes and the amount of driveway traffic.

Treatment: Control of unsignalized intersection and driveway spacing

Rural two-lane roads

Hauer reviewed a number of studies that examined the safety impact of changing access-point density on two-lane rural roads. Hauer found that, consistent with results from many previous research studies, the number of accidents on roadway segments generally increases as the density of access points for that roadway increases (*163*).

Using available data for two-lane rural roads from Transportation Research Circular 456, Hauer analyzed the accident rates and traffic volumes and concluded that based on the data, the AMF for access point densities can be represented by Equation 3-15. There was insufficient information to determine the corresponding standard error for the AMF equation.

Equation 3-15: Accident Modification Factor for access point (intersection and driveway) density (163)

$$AMF = \frac{(1.199 + 0.0047X_{after} + 0.0024X^2_{after})}{(1.199 + 0.0047X_{before} + 0.0024X^2_{before})}$$

where X is "Access Points/Mile".

Another more recent study cited by Hauer was conducted by Miaou (1996) who developed regression equations to estimate single-vehicle, off-the-road accidents resulting from changes to intersection or driveway densities on two-lane, undivided rural roads (*163*). Using results from the research study by Miaou, Hauer determined that a change in intersection densities from x to y intersections/mile on such roads resulted in the AMF shown in Equation 3-16. Similarly, a change in driveway densities from a to b driveways/mile on such roads resulted in the AMF shown in Equation 3-17. There was insufficient information to determine the functions to express the corresponding standard errors for both these AMF equations.

Equation 3-16: Accident Modification Factor for Single-vehicle, off-the-road accidents due to changes in intersection density (163)

$$AMF = e^{0.041(y-x)}$$

where x and y are expressed in intersections/mile

Equation 3-17: Accident Modification Factor for single-vehicle, off-the-road accidents due to changes in driveway density (163)

$$AMF = e^{0.010(b-a)}$$

where a and b are expressed in driveways/mile

In another similar study, Miaou re-analyzed data from a 1987 study by Zegeer et al., and using the results from this re-analysis, Hauer found that the AMF for total accidents following an increase in driveway densities assumes the form shown in Equation 3-18. There was insufficient information to determine the functions to express the corresponding standard errors for both these AMF equations.

Equation 3-18: Accident Modification Factor for total accidents due to changes in driveway density (163)

$$AMF = e^{0.0213(b-a)}$$

where a and b are expressed in driveways/mile

Hauer examined a study by Vogt and Bared that developed regression equations to estimate total accidents on roadway segments and remarked that an increase in driveway density from a driveways/mile to b driveways/mile resulted in an AMF values ranging from $e^{0.008}$ to $e^{0.012}$ (*163*). Using the final combined regression coefficient as reported in the original study, the AMF then assumes the form shown in Equation 3-19. The corresponding standard error value could not be calculated for this AMF as the necessary information was not available.

Equation 3-19: Accident Modification Factor for total accidents due to changes in driveway density (163)

$$AMF = e^{0.0084(b-a)}$$

where a and b are expressed in driveways/mile

Fitzpatrick et al. (2008) developed AMF values for driveway density along two-lane rural roads using data from Texas (*173*). For their study, 2,345 centerline miles were available and the baseline condition was set at 3 driveways per mile. Using negative binomial regression on three years of crash data, models were developed to represent the resulting effect of driveway density on crashes as shown in Equation 3-20.

Equation 3-20*: Accident Modification Factor for total accidents due to changes in driveway density (173)*

$$AMF = e^{0.0232(DD\text{-}base)}$$

where: DD = driveway/mile

base = base number of driveways (assumed at 3 driveways/mile)

Driveway density, lane width, shoulder width, segment length, and ADT were all variables considered in the development of this model.

Rural multi-lane highways

Fitzpatrick et al. (2008) also developed an AMF model for access density for rural four-lane highways *(173)*. The dataset used in the development included 402 centerline miles of roadway. The negative binomial regression produced the model shown in Equation 3-21.

Equation 3-21*: Accident Modification Factor for total accidents due to changes in driveway density (173)*

$$AMF = ((e^{0.0481(DD\text{-}base)})-1)*0.08+1$$

where: DD = driveway/mile

base = base number of driveways (assumed at 3 driveways/mile)

Median type, driveway density, lane width, shoulder width, segment length, and ADT were all variables considered in the development of this model.

Urban and suburban arterials

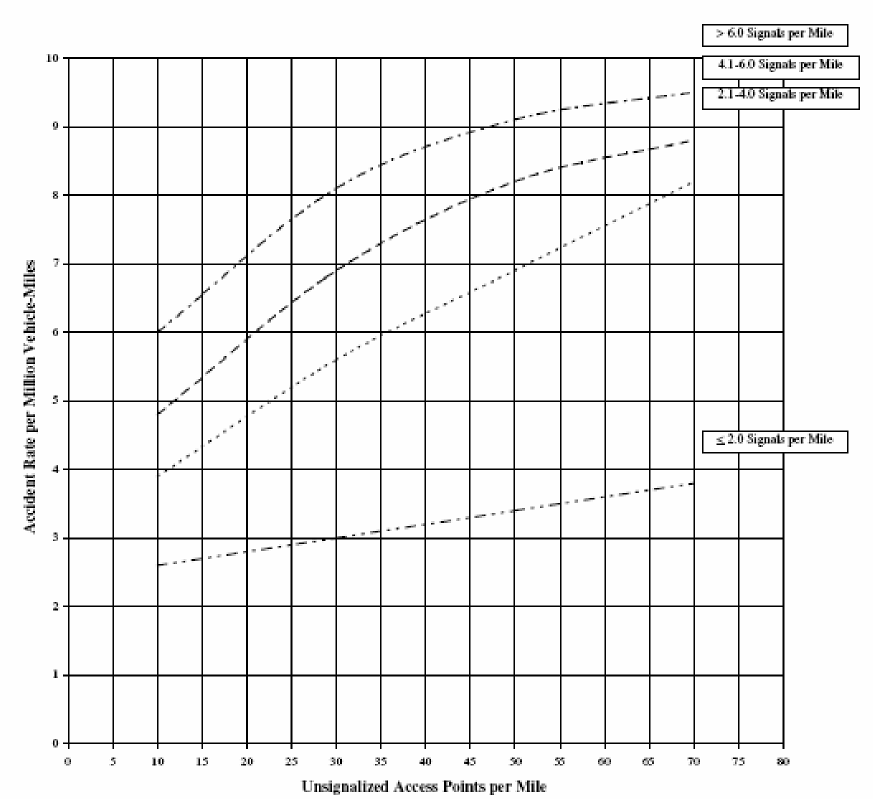
According to Gluck et al., accident rates rise with the increasing density of access points such as driveways and intersections (*164*). This trend is clearly illustrated in the accident rates derived by the authors for roadway segments with varying intersection and driveway densities as summarized in Exhibit 3-143. Although these accident rates are highly dependent on a number of other significant factors such as road geometry (e.g., lane width and presence or absence of turn lanes and physical medians), operating speeds, and driveway and intersection traffic volumes, increasing the spacing between access points and providing greater separations of conflicts will reduce the number and variety of events to which drivers must respond, thereby leading to a decrease in the potential number of overall crashes.

Exhibit 3-143: Accident rates (accidents per MVMT) by access density (164)

Unsignalized Access Points per Mile	Signalized Access Points per Mile			
	< 2.00	2.01 - 4.00	4.01 - 6.00	> 6.00
≤ 20	2.6	3.9	4.8	6.0
20.01 - 40.00	3.0	5.6	6.9	8.1
40.01 - 60.00	3.4	6.9	8.2	9.1
> 60	3.8	8.2	8.7	9.5
All	3.1	6.5	7.5	8.9

Using the results from their analysis, Gluck et al. developed functions to represent the accident rates for various access density conditions in urban and suburban areas. These functions are illustrated in Exhibit 3-144. Gluck et al. cautioned that the rates in Exhibit 3-144 may only be used to estimate the changes associated with increasing unsignalized access density at any given signal density (driveways to single-family residences should be excluded). The figure in Exhibit 3-144 cannot be used to estimate the effects of adding signals. This is because in deriving the rates, the authors used signal density as a surrogate for cross-street traffic. Following the development of the functions, Gluck et al. then devised a methodology to estimate a new accident rate for a given roadway following a change to its access density. This was achieved using Equation 3-22.

Exhibit 3-144: Estimated accident rates (Accidents per MVMT) by access density for urban/suburban areas (164)



Equation 3-22: Method to calculate accident rate (per MVMT) following changes to unsignalized access density (164)

$$\text{Projected Accident Rate} = \text{Existing Accident Rate} \times \frac{R_2}{R_1}$$

where:
R_1 is the base accident rate under prevailing access-point density conditions;
and R_2 is the base accident rate for the new access-point density conditions

As an example, assuming that a given roadway with 3 signalized intersections per mile and 18 driveways per mile has an accident rate of 7.0 accidents per MVMT. If additional driveways are added to that roadway, resulting in an increase in the unsignalized access-point density from 18 driveways per mile to 30 driveways per mile, R1 and R2 values for the base access-point density conditions are extracted from Exhibit 3-144 and the projected accident rate would be:

$$\text{Projected Accident Rate} = \text{Existing Accident Rate} \times \frac{R_2}{R_1}$$

$$= 7.0 \times \frac{5.6}{4.5}$$

$$= 8.7 \text{ acc/million VMT}$$

In essence, the R_2/R_1 ratio is analogous to the concept of AMFs as defined in this Manual. As such, the AMF values for changes to unsignalized access point densities can be directly extracted from Exhibit 3-144. There is insufficient information to determine the corresponding standard error values.

Elvik and Vaa conducted a meta-analysis of a number of studies related to the removal of private access points and driveways on urban arterials and collectors, and found that this treatment significantly reduces the number of injury accidents, regardless of the original driveway density (pg 489, (*8*)). Traffic volumes were not provided. The results from the meta-analysis are summarized in Exhibit 3-145. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

*Exhibit 3-145: Safety effectiveness of reducing private driveway densities on roadway segments(*8*)*

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Reducing private driveways per km road from 30 to 16-30	Urban	Arterials, volume not reported	All types, Injury	0.71	0.04
Elvik and Vaa, 2004	Reducing private driveways per km road from 16-30 to 6-15	Urban	Arterials, volume not reported	All types, Injury	0.69	0.02
Elvik and Vaa, 2004	Reducing private driveways per km road from 6-15 to under 6	Urban	Arterials, volume not reported	All types, Injury	0.75	0.03

Treatment: Reduce number of median crossings and intersections

Urban and suburban arterials

Gattis compared accident rates at three similar and adjacent urban roadway segments with differing access controls in place (*38*). The roadway segment with the least access control had a high density of driveways, intersecting streets and median openings; the roadway segment with a moderate level of access control had frontage roads running parallel with the main roadway segment and fewer cross streets; and the roadway segment with the highest level of access control had few median openings, driveways, and cross streets.

Gattis reported that the roadway segment with the highest level of access control also had the lowest non-intersection and intersection, angle and sideswipe accident rates but the highest intersection and non-intersection rear-end accident rates. According to Gattis, the roadway segment with the highest level of access control had PDO accident rates about half that of the other two roadway segments, and total and injury accident rates that were about forty percent less than those of the other two segments. The number of accidents and the accident rates were not provided in the study.

Rural two-lane roads; Rural multi-lane highways; Expressways

No studies found.

3.4.4. Transit Stop Placement [Future Edition]

As defined in Highway Capacity Manual (*1*), a midblock transit stop is a transit stop located at a point away from intersections.

In future editions of the HSM, this section may discuss the safety effect of various midblock transit stop placements on segments in relation to other design and operational elements (e.g., horizontal, vertical alignment, shoulder width, etc.). Potential resources are listed in Exhibit 3-146.

Exhibit 3-146: Potential resources on the relationship between transit stop placement and safety

DOCUMENT
Campbell, B. J, Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004)

3.4.5. Weather Issues

Although the weather cannot be controlled, measures to mitigate inclement weather and the resulting impact on the roadway are discussed in the following sections. Topics include adverse weather and low visibility warning systems, snow, slush and ice control, and wet pavement.

3.4.5.1. Adverse Weather and Low Visibility Warning Systems

Some transportation agencies employ advanced highway weather information systems that warn drivers of the occurrence of adverse weather, including icy conditions, or low visibility.

These systems may include on-road systems such as flashing lights, changeable message signs, static signs (e.g., “snow belt area”, “heavy fog area”), or in vehicle information systems.

Adverse weather and low visibility warning systems often rely on modern detection technology or advanced weather observations. Warnings may be given in the form of variable message signs, radio messages, or in extreme cases, temporary closing of the road. Systems warning of adverse weather or reduced visibility are most commonly used on freeways or on roads passing through mountains or other locations that may experience unusually severe weather. These systems tend to be less used on urban highways and on ordinary rural two-lane highways.

On certain mountain passes, for example in Norway, assisted platoon driving is used during heavy snowfall. Cars are stopped before entering the mountain pass. A snowplowing truck then drives first and all cars follow behind in a single platoon. Without the assistance given by the leading truck, it may be almost impossible even to see the road in heavy snowfall, which tends to go together with high winds. Visibility in this kind of weather is almost zero, as literally everything becomes white and no contours or contrasts are visible.

Dense fog presents similar problems. In dense fog, all reference points that are used for lane keeping and speed choice disappear. Traffic congestion in dense fog can be very hazardous, as cars that are moving slowly or have stopped due to congestion tend to come as a surprise. It is in dense fog on freeways that crashes involving 50 or 100 cars can occur. Crashes involving so many cars are less likely to occur when visibility is good.

The topic of this section is the safety effects of adverse weather and low visibility warning systems. Information was found only for fog warning systems, and this information may benefit from additional research.

In future editions of the HSM, this section may include information on the following treatments:

- Warnings of high winds, possibly combined with temporary speed limits
- Warnings of heavy snowfall, possibly combined with assisted platoon driving
- Warnings of slippery roads, caused for example by freezing rain
- Warning of roadway icing, particularly on bridges

Studies that have evaluated the effects of systems that warn drivers of adverse weather or low visibility have been identified in the Handbook of Road Safety Measures (Elvik and Vaa 2004) (*8*). A search of the TRANSPORT database was performed to identify the most recently published studies. Using “low visibility and road safety” as search terms, no studies were identified. Five studies concerning adverse weather and road safety were identified:

- Janoff, Davit and Rosenbaum 1982 (United States, fog warning signs)
- Edwards 1996 (Great Britain, weather related accidents)
- Hogema, van der Horst and van Nifterick 1996 (Netherlands, fog warning signs)
- Vaa 1998 (Norway, ice warning system)
- Carson and Mannering 2001 (United States, ice warning signs)

The reports of Janoff et al. and Hogema et al. state the effects of fog warning signs on the number of accidents in fog. The paper by Edwards does not describe the effects of warning devices, but deals with the importance of adverse weather in contributing to accidents. The report by Vaa was a technical feasibility study of an ice warning system, concluding that the system tested was not sufficiently reliable to be used. Carson and Mannering evaluated ice warning signs, but merely state that no statistically significant effects were found, without providing more details. Thus, only the studies of Janoff et al. and Hogema et al. provide evidence on the safety effects of warning systems.

Exhibit 3-147: Resources examined to investigate the safety effect of adverse weather and low visibility warning systems on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-28 "Pavement Marking Materials and Markers: Safety Impact and Cost-Effectiveness" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-28	On-going project.	Results not applicable. Not added to synthesis.
(Carson, J. and Mannering, F., "The Effect of Ice Warning Signs on Ice-Accident Frequencies and Severities." Accident Analysis and Prevention, Vol. 33, No. 1, Oxford, N.Y., Pergamon Press, (2001) pp. 99-109.)	Studied the effect of ice warning signs on crash frequency and severity in WA.	Suggested by 17-18(4). Too few details to be included in meta-analysis
(Weiss, A. and Schifer, J. L., "Assessment of Variable Speed Limit Implementation Issues." NCHRP 3-59, Washington, D.C., Transportation Research Board, National Research Council, (2001))	Variable speed limits	Not relevant to this section. Not added to synthesis.
(Kyte, M., Shannon, P., and Kitchener, F., "Idaho Storm Warning System Operational Test." ITD No. IVH9316 (601), Boise, Idaho Transportation Department, (2000))	Evaluated the effect of a Storm Warning System on safety; did not analyze crashes, used speed a surrogate for safety	Suggested by 17-18(4). No accident data, not added to synthesis.
(Vaa, T. Evaluering av system for isvarsling. SINTEF rapport A98558. Trondheim, SINTEF, (1998))	Technical feasibility study of an ice warning system.	Does not describe effects of warning devices. Not added to synthesis.
(Hogema, J. H. and van der Horst, R., "Evaluation of A16 Motorway Fog-Signaling System with Respect to Driving Behavior." Washington, D.C., Transportation Research Board, National Research Council, (1997) pp. 63-67.)	Evaluated the effect of an automatic fog-signaling system on driver behavior in the Netherlands; used surrogate measures for safety	Suggested by 17-18(4). This paper uses surrogate measures for safety; 1996 paper by same authors rely on accident data and was included
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	A literature review and survey of Canadian jurisdictions, yielded recommendations for non-enforcement speed management measures	No AMFs. Not added to synthesis.
(*166*) (Hogema, J. H., van der Horst, R., and van Nifterick, W., "Evaluation of an automatic fog-warning system." Traffic Engineering and Control, Vol. 37, No. 11, London, United Kingdom, Hemming Information Services, (1996) pp. 629-632.)	Evaluated the effect of an automatic fog-signaling system on driver behavior in the Netherlands.	Added to synthesis.
(Edwards, J., "Weather-related road accidents in England and Wales: A spacial analysis." Journal of Transport Geography 4:201-212. (1996))	Reviewed adverse weather and road safety.	Does not describe effects of warning devices. Not added to synthesis.
(Kulmala, R. and Rama, P., "Safety Evaluation in Practice: Weather Warning Systems." Smart Vehicles Lisse, Netherlands, Swets & Zeitlinger, (1995))	Studied the effect of a Road Weather Warning System in Finland on speed and headway	Suggested by 17-18(4). No accident data. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Office of Technology Applications, "Ice Detection and Highway Weather Information Systems." FHWA-SA-93-053, Washington, D.C., Federal Highway Administration, (1993))	Reports the results of evaluations conducted by 8 states of their ice detection and highway weather information systems; potential for crashes due to icy conditions was one of the aspects evaluated	Suggested by 17-18(4). Limited qualitative information. Not added to synthesis.
(*167*) (Janoff, M. S., Davit, P. S., and Rosenbaum, M. J., "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 11." Adverse Environmental Operations FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Before-and-after study, employing accidents not occurring in fog as comparison group	Added to synthesis.

Treatment: Implement fog warning signs

The findings of the studies of Janoff et al. (1982) and Hogema et al. (1996) have been synthesized. Janoff et al. is a before-and-after study, employing accidents not occurring in fog as a comparison group (*167*). Janoff et al. was rated low for quality and the standard error was adjusted by a factor of 3. Hogema et al. is also a before-and-after study, but the authors employed a comparison group in addition to using non-fog accidents as a comparison (*166*). The study was rated as high quality, and the standard error of the estimate of effect was adjusted by a factor of 1.2.

The summary estimate of effect based on both studies is a reduction in fog accidents of 77% (t = 0.227, s = 1.005). Although the number of accidents in fog went down by almost 80%, the reduction was not statistically significant and the resulting standard error is quite large. The size of the reduction makes it unlikely, however, that it is entirely attributable to chance variation.

3.4.5.2. Snow, Slush, and Ice Control

It is generally accepted that the presence of snow, slush or ice on the road surface increases the accident rate. By improving the standards of winter maintenance, it may be possible to contain, or ideally speaking, eliminate the increase in accident rate, thus making travel as safe in winter as it is in summer. A number of measures are used to control snow, slush and ice. This section reviews the effects of these measures on road safety. The review is based on an updated version of the meta-analysis reported in Elvik and Vaa's "Handbook of Road Safety Measures" (*8*).

This section discusses the safety effects of measures designed to control snow, slush or ice. First, a discussion of the safety impact of the presence of snow, slush or ice on the roadway surface is presented. Then, the following treatments have been included in the review:

- Snow clearance (plowing)
- Use of sand to improve friction
- Use of salt to prevent snow or ice from forming or from sticking to the road surface
- Use of salt as an accident blackspot measure
- Increasing maintenance preparedness (shorter response time)
- Increasing standards for winter maintenance
- Installing snow screens in areas exposed to snowdrifts

Exhibit 3-148: Resources examined to investigate the safety effect of snow, slush and ice control on roadway segments

DOCUMENT	DESCRIPTION	COMMENT
(*8*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis updated for the purposes of the HSM.	Added to synthesis.
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Synthesis of a variety of reports on the reduction of crashes on horizontal curves.	No new information. Not added to synthesis.
(Khattak, A. J. and Knapp, K. K., "Interstate Highway Crash Injuries During Winter Snow and Non-Snow Events." Washington, D.C, 80th Annual Meeting of the Transportation Research Board, (2001))	Compare crashes and occupant injuries reported on Interstate highways in Iowa during winter snow event periods to winter non-snow event periods; controlled for other factors.	Suggested by 17-18(4). Deals with snow as risk factor; not relevant for this section. Not added to synthesis.
(Friar, S. and Decker, R., "Evaluation of a Fixed Anti-Icing Spray System." Transportation Research Record, No. 1672, Washington, D.C., Transportation Research Board, National Research Council, (1999) pp. 34-41.)	Before and after study of the effect of an anti-icing system on crashes; one location in Utah	Suggested by 17-18(4). Added to meta-analysis of Elvik (2004).
(Gilfillan, G., "Road Safety Benefits Of Liquid Anti-Icing Strategies and Agents." Kamloops, British Columbia, Canada, Insurance Corporation of British Columbia, (1999))	An analysis of three years of historical collision data based on individual roadway test segments	Added to meta-analysis of Elvik (2004).
(Hanbali, R. M., "Criterion for Evaluating the Effectiveness of Winter Road Maintenance on Traffic Safety." Toronto, Ontario, Canada, International Road Federation XIII World Meeting, (1998))	Analyzes the effect of snow and icy conditions and their countermeasures on traffic safety	Suggested by 17-18(4). Not enough data to include in meta-analysis.
(Kulmala, R. and Rama, P., "Safety Evaluation in Practice: Weather Warning Systems." Smart Vehicles Lisse, Netherlands, Swets & Zeitlinger, (1995))	A report based on the implementation of an experimental design at three locations and the capture of the results	No AMFs. Not added to synthesis.
(Savenhed, H., "Relationship Between Winter Road Maintenance and Road Safety." 399A, Swedish National Road and Transport Research Institute (VTI), (1995))	Evaluated the crash risk of before and after winter road maintenance	Suggested by 17-18(4). 1994 VTI-report by same author included in synthesis.
(Sävenhed, H., "Relation between Winter Road Maintenance and Road Safety." Seefeld, Austria, IXth PIARC International Road Congress, (1994))	Evaluated the crash risk of before and after winter road maintenance	Added to meta-analysis of Elvik (2004).
(Alger, R. G., Beckwith, J. P., and Adams, E. E., "Comparison of Liquid and Solid Chemicals for Anti-Icing Applications on Pavements." Transportation Research Record 1442, Washington, D.C., (1994) pp. 162-169.)	Review and summary of the data acquired from tests designed to assess the anti-icing properties of several chemicals that are potential candidates for winter highway maintenance	Not enough data to include in meta-analysis.
(Hanbali, R. M., "Economic Impact of Winter Road Maintenance on Road Users." Transportation Research Record 1442, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 151-161.)	Evaluated the effect on safety of winter road maintenance operations	Suggested by 17-18(4). Not enough data to include in meta-analysis.

Discussion: Safety impact of the presence of snow, slush or ice on the roadway surface

In most jurisdictions, standards have been developed for the use of these measures. A standard may state, for example, that snow should be cleared from the road surface before snow depth exceeds 2 inches (5 cm). Standards for snow clearance very often depend on traffic volume and on the transport function a road serves. The strictest standards typically apply to freeways or arterial roads, whereas no standard at all may have been developed for minor access roads in residential areas. Depending on the intensity of snowfall, a certain standard for maximum snow depth implies a certain maximum response time before snow is cleared. If snow falls very intensely, the response must be quicker than if there are only scattered snowflakes.

Salt, also known as chemical de-icing, is generally used as a preventive measure, to prevent snow from sticking to the road surface. Ideally speaking, salted roads should have a bare road surface throughout the winter. In cold winter climates, this is not feasible, as salt is effective only at temperatures above about 21F (or -6°C).

It is important to distinguish between the short-term effects of snow, slush or ice control and the effects throughout an entire winter season. The difference between short-term and long-term effects can be shown by means of an example.

*Exhibit 3-149: Short term effect of snow clearance at low preparedness (*8*)*

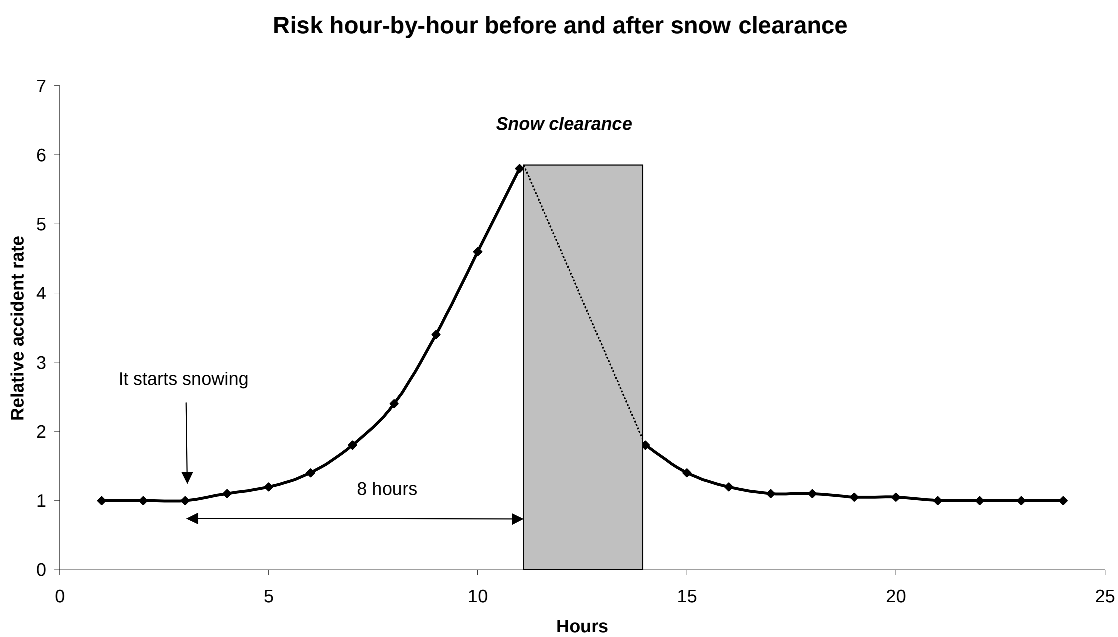
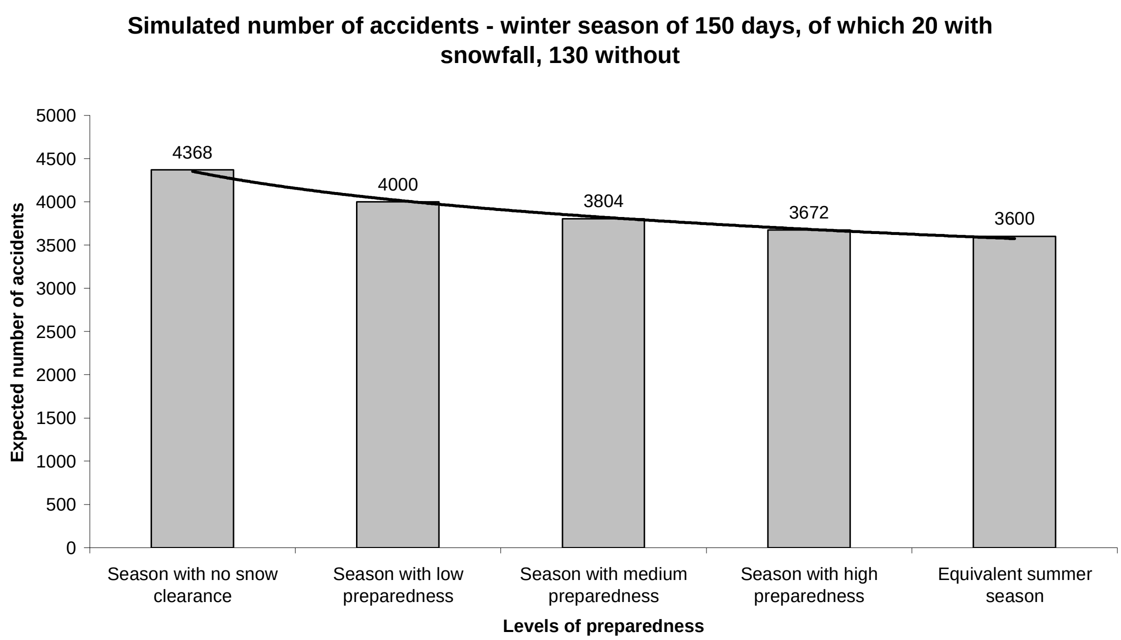


Exhibit 3-149 shows the typical development hour-by-hour in accident rate during snowy weather. As it starts to snow, road surface conditions get worse and the accident rate starts to rise. In the example given in Exhibit 3-149, snow clearance begins eight hours after it starts snowing; this would not be an abnormal delay, for example on a weekend night. Snow is then cleared and the accident rate drops drastically. Traffic wears down whatever snow might be left after clearance, thus bringing the accident rate back to the level before it started to snow. If it is assumed that all hours have the same traffic volume (which is obviously unrealistic for any given day, but perhaps not unrealistic in the long run, as it can start snowing at any time of the day), the effect of snow clearance in Exhibit 3-149 can be estimated as an accident reduction of 49%. The eleven hours before snow clearance have then been compared to the eleven hours after snow clearance. (*8*)

If maintenance crews operate at a higher state of preparedness, they may perhaps start clearing the road of snow after four hours, rather than eight. The rise in accident rate is then broken off at an earlier stage. The effect of snow clearance during the first 11 hours after it was performed, compared to the last 11 hours before, can then be estimated as an 8% accident reduction, again assuming that all hours carry the same amount of traffic. Thus, somewhat counter-intuitively, a high state of preparedness is associated with a smaller estimated short-term effect on accidents than a low state of preparedness. The explanation of this lies in the fact that conditions do not get as bad before action is taken in the state of high preparedness as they do in the state of low preparedness. (*8*)

The effects of different standards of winter maintenance on accidents during the whole winter season are much smaller than the short-term effects. Exhibit 3-150 shows simulated total numbers of accidents for a winter season based on different levels of preparedness, all based on the model presented in Exhibit 3-149.

Exhibit 3-150: Simulated effects of different levels of preparedness in winter maintenance – whole season



In this example, it has been assumed that the winter season lasts for 150 days (defined as days during which temperature drops below freezing (32F, 0°C). There is snowfall on 20 days, and no snow on 130 days. In the example given in Exhibit 3-150, maintaining a high state of preparedness compared to maintaining a low state of preparedness during the whole season is associated with an accident reduction of about 8% (from Exhibit 3-150: high preparedness = 3672 expected accidents, low preparedness = 4000 expected accidents; then 3672/4000 = 0.92). The effects will increase as a function of the duration and severity of the winter season. The longer it lasts, and the more often there is adverse weather, the more important becomes the standard of winter operations for the safety of traffic.

Treatment: Take measures to control snow, slush or ice

All road types

Exhibit 3-151 lists the studies that serve as the basis for the estimates of effect presented in this section. In total, 24 studies containing 188 estimates of effect have been retrieved. The largest number of studies refers to the use of salt. There are 14 studies that have evaluated the safety effects of salting roads. Six studies have evaluated the effects of standards for winter operations, such as the depth of snow tolerated before clearance is started. Finally four studies have evaluated the effects of several types of snow or ice control, including snow clearance, use of salt or sanding.

Some studies have employed more than one type of design. These studies are listed once for each of the designs they have employed, since different study designs embody different levels of control for confounding factors.

*Exhibit 3-151: Studies that have evaluated effects on road safety of chemical de-icing, standards for winter operations, and other winter operations (*8*)*

Study	Country	Design	Number of estimates
Studies that have evaluated use of salt (chemical de-icing)			
Väg- och vattenbyggnad 1972	Finland	Before-after with comparison group	4
Andersson 1978	Sweden	Before-after with comparison group	12
Andersson 1978	Sweden	Case-control study	9
Brüde and Larsson 1980	Sweden	Case-control study	18
Lie 1981	Norway	Matched case-control study	45
Öberg et al 1985	Sweden	Before-after with comparison group	4
Möller 1988	Sweden	Case-control study	9
Nilsson and Vaa 1991	Norway	Before-after with comparison	6
Öberg et al 1991	Sweden	Before-after with comparison	3
Kallberg 1993	Finland	Before-after with comparison	2
Öberg 1994	Sweden	Before-after with comparison	1
Sakshaug and Vaa 1995	Norway	Before-after with comparison	1
Sakshaug and Vaa 1995	Norway	Simple before-after	2

Sakshaug and Vaa 1995	Norway	Case-control study	2
Kallberg 1996	Finland	Before-after with comparison	1
Friar and Decker 1999	United States	Before-after with comparison	1
Gilfillan 2000	Canada	Simple before-after	2
Studies that have evaluated standards for winter operations			
Ragnøy 1985	Norway	Comparative study	9
Bertilsson 1987	Sweden	Simple before-after	4
Schandersson 1988	Sweden	Comparative study	36
Eriksen and Vaa 1994	Norway	Before-after, matched comparison	2
Vaa 1996	Norway	Before-after, matched comparison	2
Studies that have evaluated other winter operations			
Tabler and Furnish 1982	United States	Simple before-after (snow screens)	8
Björketun 1983	Sweden	Matched before-after (preparedness)	6
Schandersson 1986	Sweden	Simple before-after (several actions)	6
Sävenhed 1994	Sweden	Simple before-after (several actions)	1

The quality of the studies varies. No study has been rated as high quality; 86 estimates of effect have been rated as medium-high quality, 81 estimates of effect have been rated as medium-low quality and 21 estimates of effect have been rated as low quality. The standard errors of estimates of effect in each study have been adjusted by a factor of 1.8 for medium-high quality estimates based on before-and-after studies, 2.2 for medium-low quality estimates of effect, and 3 for low quality estimates of effect based on before-and-after studies. For other study designs, such as case-control studies or comparative studies, the corresponding correction factors for the standard error were 2 for medium-high quality estimates, 3 for medium-low quality estimates, and 5 for low quality estimates of effect. The adjustment factor for the standard error was 1.8 for 49 estimates of effect, 2 for 37 estimates of effect, 3 for 100 estimates of effect and 5 for 2 estimates of effect.

Few of the studies provide a detailed description of the types of road or traffic environment to which the study results apply. Many studies refer to fairly large road systems, in some cases comprising several thousand kilometres. In these cases, it is probably reasonable to assume that all types of roads are included, both urban and rural, as well as freeways. A few studies, notably those of Eriksen and Vaa (1994), Vaa (1996) and Gilfillan (2000), have evaluated programmes for improving winter operations in cities (as reviewed in Elvik and Vaa (2004) (*8*)). The cities studied were Trondheim in Norway and Kamloops in British Columbia, Canada.

Estimates of effect generally refer to all types of accidents (i.e., both single vehicle and multiple, involving all types of road users). Some studies identify accidents according to road surface condition. The most commonly made distinction is between snow or ice-covered road surfaces and bare road surfaces. No study makes a clear distinction between snow-covered road surfaces and ice-covered road surfaces.

Nearly all studies were conducted in the Scandinavian countries. The length and severity of the winter season varies substantially between regions of these countries. In the south of Sweden, for example, there may not be any snow at all during winter, and only a few days with freezing rain or ice on the road. In the northern parts of Finland, Norway and Sweden, snow usually falls in October and remains on the ground until late April. Most roads in these areas, at least in rural areas, are fully or partly covered by snow throughout the winter.

Exhibit 3-152 reports summary estimates of effect for various measures taken to control snow, slush or ice. Effects are stated as odds ratios. The standard errors have been adjusted as explained above. The estimates are based on conventional meta-analysis. The number of estimates underlying each summary estimate is shown in parentheses. Accident severity is stated if it was specified in the studies serving as sources for the summary estimates of effect. The structure of the results was such that a meta-regression analysis was not judged to be informative in this case.

*Exhibit 3-152: Summary estimates of the effects on accidents of snow, slush and ice control (*8*)*

Measure taken	Specification of effect	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Short-term effects of all measures to control snow, slush or ice (all accidents)			
All measures	First 12 hours (1)	0.500	0.197
	First 24 hours (6)	0.707	0.240
	First 96 hours (2)	0.955	0.189
Effects during the whole winter season of raising standards for winter operations			
Raising standards	Injury accident (31)	0.891	0.022
	PDO-accidents (22)	0.734	0.020
Effects of use of salt (chemical de-icing) during the whole winter season (baseline = no salt)			
Introduction of salt	Injury accidents (42)	0.852	0.094
	PDO-accidents (6)	0.919	0.083
Termination of salt	Injury accidents (6)	1.116	0.136
	PDO-accidents (5)	0.998	0.121
Effects of snow fences and higher state of preparedness for the whole winter season			
Snow fences (6%)	All accidents	0.894	0.256
Higher preparedness	All accidents	0.922	0.068*

* NOTE: Based on a single study only; general validity is highly uncertain, even if standard error is small

The short-term effects of measures taken to control snow, slush or ice (this includes snow clearance, spread of sand, and spread of salt) are largest during the first 12 hours after the measures were taken, and then decline. Only a very small effect remains after 96 hours (Exhibit 3-152). This pattern conforms to what one would expect the effects of winter operations to be. The baseline for these estimates of effect is a before-period of equal duration to the after period (i.e., 12 hours, 24 hours or 96 hours). During the before period, there will typically have been snow storms or other adverse weather conditions. (*8*)

The road system will usually have been classified into one of a limited number of classes, maybe 4 or 5, with respect to the minimum standards for winter operations. Raising the standards for winter operations by one class is associated with a reduction of the number of injury accidents of about 10% and a reduction of the number of property-damage-only accidents of about 25% (Exhibit 3-152). It should be noted that many of the estimates serving as the basis for the summary estimate come from cross-section studies that did not adequately control for confounding factors. The accident samples were large in many studies; hence the standard error is small. (*8*)

As an example of the standards used and what it means to raise standards by one class, Exhibit 3-153 provides details of the standards for winter operations used on national highways in Norway.

Exhibit 3-153: Standards for winter maintenance on national roads in Norway

Standards	**Class 4 AADT <500**	**Class 3 AADT 501-1500**	**Class 2 AADT 1501-3000**	**Class 1 AADT >3001**
Strategy A: Snow or ice permitted to form on road surface				
Maximum snow depth before clearance (dry snow, cm)	15	12	10	7
Maximum snow depth before clearance (wet snow, cm)	12	8	7	6
Spread of sand if friction is below 0.25	Within 4 hours at critical points	Within 4 hours, whole road	Within 2 hours, whole road	Within 2 hours, whole road
Strategy B: Keep road surface bare (no snow or ice)				
Maximum snow depth before clearance (dry snow, cm)	Strategy not used	Strategy not used	10	7
Maximum snow depth before clearance (wet snow, cm)	Strategy not used	Strategy not used	7	6
Preventive salting	Not performed	Not performed	Applied if friction is expected to drop below 0.4	Applied if friction is expected to drop below 0.4
Road surface should be bare within N hours after snowfall	Snow on road surface permitted	Snow on road surface permitted	Within 6 hours after snowfall	Within 4 hours after snowfall Within 2 hours after snowfall (AADT >5000)

The introduction of preventive salting is associated with a reduction of the number of accidents. The term preventive salting refers to the spread of salt before it starts to snow, in order to prevent snow from sticking to the road surface. If salting is terminated, the number of injury accidents appears to increase, whereas the number of property-damage-only accidents remains unchanged (Exhibit 3-152). The baseline for these estimates is roads that are not salted at all in winter.

Snow fences may be installed on mountain passes that are exposed to snow drifts. If 6% of the highway length is covered by snow fences, there is a reduction of snow-related accidents of about 10% (Exhibit 3-152). This estimate refers to a mountain pass that was particularly exposed to snow drifts across the road. This estimate of safety effect cannot necessarily be extrapolated to other percent coverage of snow fences.

Raising the state of preparedness, for example by having maintenance crews on stand-by duty, or by having inspection vehicles driving around the road system, is associated with an accident reduction throughout the winter season of about 8% (Exhibit 3-152). The estimate is based on a single study only and its general validity is therefore highly uncertain, even if the standard error is small.

3.4.5.3. Wet Pavement [Future Edition]

In future editions of the HSM, this section may discuss the safety effect of drainage characteristics, hydroplaning remediation, high-friction pavements (e.g., at specific curve location), and other elements related to wet pavement. Potential resources are listed in Exhibit 3-154.

Exhibit 3-154: Potential resources on the relationship between wet pavement and safety

DOCUMENT
NCHRP 17-28: Pavement Marking Materials and Markers: Safety Impact and Cost-Effectiveness (http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-28)
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))
(Hanley, K. E., Gibby, A. R., and Ferrara, T. C., "Analysis of Accident Reduction Factors on California State Highways." Transportation Research Record, No. 1717, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 37-45.)
(Kyte, M., Shannon, P., and Kitchener, F., "Idaho Storm Warning System Operational Test." ITD No. IVH9316 (601), Boise, Idaho Transportation Department, (2000))
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))
(Kulmala, R. and Rama, P., "Safety Evaluation in Practice: Weather Warning Systems." Smart Vehicles Lisse, Netherlands, Swets & Zeitlinger, (1995))
(Fambro, D. B., Nowlin, R. L., Warren, S. P., Lienau, K. A., Mounce, J. M., Bligh, R. P., Mak, K. K., and Ross, H. E., "Geometric Design Guidelines for Suburban High-Speed Curb and Gutter Roadways." FHWA/TX-95/1347-1F, College Station, Texas A&M University, (1995))
(Dahir, S. H. and Gramling, W. L., "NCHRP Synthesis of Highway Practice Report 158: Wet-Pavement Safety Programs." Washington, D.C., Transportation Research Board, National Research Council, (1990))
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))

3.4.6. Pavement Materials [Future Edition]

In future editions of the HSM, this section may include discussion of the safety impact of pavement surface deterioration, changes to the coefficient of surface friction, and surface rehabilitation, for different surface materials (e.g., asphalt concrete, Portland cement concrete, gravel, tar & gravel, dirt, interlock bricks, grooved pavement, textured roads, etc.). Potential resources are listed in Exhibit 3-155.

Exhibit 3-155: Potential resources on the relationship between pavement materials and safety

DOCUMENT
NCHRP 17-28: Pavement Marking Materials and Markers: Safety Impact and Cost-Effectiveness (http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-28)
NCHRP 17-26: Methodology to Predict the Safety Performance of Urban and Suburban Arterials (http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26)
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Collisions at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Torbic, D. J., Harwood, D. W., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 7: A Guide for Reducing Collisions on Horizontal Curves." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Council, F. M., McGee, H., Prothe, L., and Eccles, K. A., "NCHRP Report 500 Volume 6: A Guide for Addressing Run-off-Road Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))
(Bray, JS. (2003) "Skid Accident Reduction Program (SKARP): Targeted Crash Reductions." Institute of Transportation Engineers (ITE) 2003 Technical Conference and Exhibit. Fort Lauderdale, Florida, USA)
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))
(Hauer, E., "Shoulder Width, Shoulder Paving and Safety." (2000))
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))
(Gharaibeth, N. G., Hicks, J. E., and Hall, J. P., "Analysis of Accidents, Traffic and Pavement Data." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 396-402.)
(Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995), Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))
(Ligon, C. M., Carter, E. C., Joost, D. B., and Wolman, W. W., "Effects of Shoulder Textured Treatment on Safety." FHWA/RD-85/027, Washington, D.C., Federal Highway Administration, (1985))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
(Dawson, R. F. and Oppenlander, J. C., "General Design." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 11, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))

DOCUMENT
(Dearinger, J. A. and Hutchinson, J. W., "Cross Section and Pavement Surface." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 7, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))

3.4.7. Animals [Future Edition]

In future editions of the HSM, this section may address treatments to mitigate the presences of wild animals along roadway segments (e.g., deer, moose, etc.) to reduce crashes between motor vehicles and wild animals. Potential resources are listed in Exhibit 3-156.

Exhibit 3-156: Potential resources on the relationship between animals and safety

DOCUMENT
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))

References

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2. Hauer, E., "Lane Width and Safety." (2000)
3. Hauer, E., Council, F. M., and Mohammedshah, Y., "Safety Models for Urban Four-Lane Undivided Road Segments." (2004)
4. Bauer, K. M., Harwood, D. W., Hughes, W. E., and Richard, K. R., "Safety Effects of Using Narrow Lanes and Shoulder-Use Lanes to Increase the Capacity of Urban Freeways." 83rd Transportation Research Board Annual Meeting, Washington, D.C., (2004)
5. Harwood, D. W., Rabbani, E. R., Richard, K. R., McGee, H. W., and Gittings, G. L., "NCHRP Report 486: Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects." Washington, D.C., Transportation Research Board, National Research Council, (2003)
6. Huang, H. F., Stewart, J. R., and Zegeer, C. V., "Evaluation of Lane Reduction "Road Diet" Measures on Crashes and Injuries." Transportation Research Record, No. 1784, Washington, D.C., Transportation Research Board, National Research Council, (2002) pp. 80-90.
7. Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000)
8. Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004)
9. Hauer, E., "Shoulder Width, Shoulder Paving and Safety." (2000)
10. Hadi, M. A., Aruldhas, J., Chow, L., and Wattleworth, J., "Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression." Transportation Research Record 1500, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 169-177.
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155. Berchem, S. and Somerfeld, W. O., "Unique Roadway Design Reduces Bus-Bike Conflicts." TR News, No. 177, Washington, D.C., Transportation Research Board, National Research Council, (1985) pp. 2-3.

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157. City of Eugene, "18th Avenue Bike Lanes - One Year Report, Memorandum to City Council." Eugene, Oregon, (1980)

158. Lott, D. F. and Lott, D. Y., "Differential Effect of Bicycle Lanes on Ten Classes of Bicycle-Automobile Accidents." Transportation Research Record 605, Washington, D.C., Transportation Research Board, National Research Council, (1976) pp. 20-24.
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162. Preston, H. and Schoenecker, T., "Safety Impacts of Street Lighting at Rural Intersections." 1999, St. Paul, Minnesota Department of Transportation, (1999)
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164. Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999)
165. Gattis, J. L., "Comparison of Delay and Accidents on Three Roadway Access Designs in a Small City." Transportation Research Board 2nd National Conference, Vail, Colo., (1996) pp. 269-275.
166. Hogema, J. H., van der Horst, R., and van Nifterick, W., "Evaluation of an automatic fog-warning system." Traffic Engineering and Control, Vol. 37, No. 11, London, United Kingdom, Hemming Information Services, (1996) pp. 629-632.
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173. Fitzpatrick, K., Park, E.S., and Schneider, W.H., "Potential Driveway Density Accident Modification Factors for Rural Highways Using Texas Data," Transportation Research Board 87th Annual Meeting, Washington D.C., (2008)

Chapter 4: Intersections

Chapter 4. Intersections

CONTENTS

EXHIBITS

EQUATIONS

4.1. Safety Effects of Intersection Design Elements

An intersection is the at-grade crossing of two highways, and can be three-, four-, or multi-leg, or take the form of a roundabout. The following sections describe the safety effects of the design and operations of intersections, including roundabouts. Pedestrian and bicyclist considerations are discussed, as well as other intersection elements, such as illumination.

4.1.1. Intersection Types

As early as 1970, Box pointed out that accident statistics clearly indicate that accidents at intersections are a national problem. However, since the area of influence of an intersection often extends far beyond the intersection itself, the issue of defining what constitutes an intersection accident is sometimes a problem in itself (*1*). According to AASHTO, an intersection is defined by both its physical and functional areas(*2*). This functional area extends both upstream and downstream from the physical intersection area and includes any auxiliary lanes and their associated channelization. For example, some agencies may define an intersection accident as one which occurs within the intersection crosswalk limits while other agencies may consider all accidents within 100 or 200 ft of an intersection as being intersectional (*1*).

The discussion in this section will also cover the implementation of roundabouts for different traffic volume ranges. When results from before-after studies are available, the “before” traffic control type is also discussed. Where possible, the safety impacts of the road safety treatments on motorcyclists will be considered. The distinction between road types and urban versus rural settings is particularly critical in this section, since the safety of a multi-lane intersection is not likely to be comparable with the safety of a single lane intersection given the different volume and capacity needs, and given the policies that are likely to govern the intersection design.

For a more detailed overview of the elements that are related to intersection design and types of intersection configurations in use, the reader is directed to AASHTO’s “Green Book” (*2*), as well as a recent study by Fitzpatrick and Wooldridge (*3*). In addition to conventional intersection designs, this section also discusses the safety impacts of alternative intersection designs such as tapered offset left-turn lanes and the construction of indirect left-turn road safety treatments. These include median U-turn crossovers, super street median crossovers, quadrant roadway intersections, split intersections, and continuous flow intersections. The reader is directed to the recently available FHWA Signalized Intersection Guide for further information, available at http://www.tfhrc.gov/safety/pubs/04091/index.htm.

This section examines the safety effects of the various types of intersections, including signalized and unsignalized 3-leg, 4-leg, and multi-leg intersections and roundabouts. The discussion in this section excludes any consideration for approach roadway elements such as lanes (number, width, etc.), shoulders and sidewalks, and medians since these topics are addressed in Section 4.1.2.

FHWA’s Roundabout Guide contains additional general information on design and operational issues concerning roundabouts. Given that a large number of studies, which investigate the safety impacts of various road safety treatments at intersections, are related to pedestrians and bicyclists, readers may also refer to Section 4.3 Pedestrian and Bicyclist Safety.

Exhibit 4-1: Resources examined to investigate the safety effect of intersection types

DOCUMENT	DESCRIPTION	COMMENT
(*119*) (Jagannathan, R., Gimbel, M., Bared, J.G., Hughes, W.E., Persaud, B., and Lyon, C., Safety Comparison of Jug Handle Intersections and Conventional Intersections, *Transportation Research Record* 1953, 2006, pp. 187-200.)	Study compared the safety of 44 New Jersey Jug Handle intersections with 50 conventional signalized intersections using cross-sectional regression models	Added to synthesis. Information was not sufficient to develop AMFs and standard errors.
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities	Added to synthesis. Only qualitative discussion of safety impacts presented. No quantitative evidence of quantified safety impacts found.
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Reference discusses potential safety impacts of reducing intersection skew and providing left-turn lanes with positive offsets for older drivers	Not added to synthesis. No AMFs or other quantified evidence of safety improvements. Some material on offset left-turn lanes may be relevant to other sections.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results may be added if relevant when available.
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Reference suggested by NCHRP 17-18(4). Added to synthesis. Results from meta-analysis used to calculate t and s values.
(McGee, H., Taori, S., and Persaud, B. N., "NCHRP Report 491: Crash Experience Warrant for Traffic Signals." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Study investigated the safety of signalized and stop-controlled intersections using an Empirical Bayes before-after study approach.	Not added to synthesis since material is more relevant to traffic control at intersections.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Report is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections	Not added to synthesis because of lack of quantitative evidence of safety effects.
(*6*) (Bared, J. G. and Kaisar, E. I., "Advantages of Offset T-Intersections with Guidelines." Moscow, Russia, Proc. Traffic Safety on Three Continents, (2001))	Study investigated the safety impact of converting three- and four-leg intersections by offsetting them and creating two offset T- intersections.	Plots showing crash reduction functions added to synthesis. There is insufficient information in reference to calculate s values.

DOCUMENT	DESCRIPTION	COMMENT
(Xu, L., "Right Turns Followed by U-Turns vs. Direct Left Turns: A Comparison of Safety Issues." No. 11, (2001) pp. 36-43.)	Cross-sectional study comparing accident rates and accident frequencies between direct left-turns and an alternative left-turn design (i.e. right-turn, followed by U-turn)	Reference suggested by NCHRP 17-18(4). Not added to synthesis. Treatment being examined is the type of left-turn configuration and not directly related to the design of the intersection itself. Reference is more relevant intersection operations.
(Bauer, K. M. and Harwood, D. W., "Statistical Models of At-Grade Intersections - Addendum." FHWA-RD-99-094, McLean, Va., Federal Highway Administration, (2000))	Used crash data to develop statistical models of the relationship between traffic crashes and highway geometric elements for at-grade intersections	Reference suggested by NCHRP 17-18(4). Not added to synthesis. Accident models for three- and four-leg urban and rural intersections were developed and the information provided is more relevant to Approach Roadway Elements section
(*7*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Study presents an algorithm for predicting the safety performance of various factors for roadway segments and for at-grade intersections on rural two-lane highways	Added to synthesis. Highly relevant reference for Approach Roadway Elements section as well.
(Vogt, A., "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized." FHWA-RD-99-128, McLean, Va., Federal Highway Administration, (1999))	Crash models and crash reduction factors were developed for rural three- and four-leg rural intersections on four-lane highways, stop-controlled on the minor legs; and signalized rural intersections of two-lane roads.	Not added to synthesis. Reference is more relevant to Approach Roadway Elements section.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Reference reviewed existing research and provided guidelines on highway engineering improvements that would help older drivers and pedestrians	Not added to synthesis. No AMFs or other quantitative evidence of safety impacts found
(Kulmala, R., "Safety at Rural Three- and Four-Arm Junctions: Development and Application of Accident Prediction Models." 233, Espoo, Finland, VTT Technical Research Centre of Finland, (1995))	Before-After study of the safety effectiveness of several geometric design elements at rural three- and four-leg intersections	Not added to synthesis. More relevant to Approach Roadway Elements section.
(Kuciemba, S. R. and Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume V - Intersections." FHWA-RD-91-048, Washington, D.C., Federal Highway Administration, (1992))	Report briefly discusses nine studies (1972 to 1988) of the relationship between intersections and safety.	Not added to synthesis. No AMFs or other quantitative evidence of safety impacts found

DOCUMENT	DESCRIPTION	COMMENT
(Corben, B. F., "Crashes at Traffic Signals: Guidelines for a Traffic Engineering Safety Program of Replacing Selected Intersection Signals with Roundabouts." 7, Victoria, Australia, VicRoads and Transport Accident Commission, (1989))	Study's objective was to develop traffic safety engineering guidelines for when and where to replace existing traffic signals with roundabouts.	Not added to synthesis. No relevant information.
(Box, P. C., "Intersections." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 4, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reference reviews studies relating safety to elements of intersections, including geometric layout, left-turn lanes, traffic controls, signing, and turn restrictions among others	Not added to synthesis. No AMFs or other quantitative evidence of safety impacts found.

Exhibit 4-2: Resources examined to investigate the safety effect of roundabouts

DOCUMENT	DESCRIPTION	COMMENT
(*120*) (Rodegerdts, L. A., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., List, G., Flannery, A., Troutbeck, R., Brilon, W., Wu, N., Persaud, B., Lyon, C., Harkey, D., and Carter, E. C., "NCHRP Report 572: Applying Roundabouts in the United States." Washington, D.C., Transportation Research Board, National Research Council, (2007))	Before-after study of the effect of crashes at 55 intersections that were converted to roundabouts (36 were previously two-way stop controlled, 10 were all-way stop controlled, and 9 were controlled by signals); includes rural, suburban, and urban environments	Added to synthesis. t and s values included in Master summary table.
(*121*) (Nambisan, S. S. and Parimi, V. "A Comparative Evaluation of the Safety Performance of Roundabouts and Traditional Intersection Controls", *ITE Journal*, March 2007).	This study compared the crash rates of 6 roundabouts with 8 stop and signalized intersections in Las Vegas.	Not added to synthesis because other studies used more defensible methods.
(*122*) (De Brabander, B. and Vereeck, L., Safety Effects of Roundabouts in Flanders: Signal Type, Speed Limits, and Vulnerable Road Users, *Accident Analysis and Prevention*, 39 (2007), pp. 591-599.)	Before-after study of the effect of injury crashes at 95 roundabouts in the Flanders area of Belgium. The EB approach was used but traffic volume was not available and hence safety effects could not be modeled using safety performance functions.	Added to synthesis, but results from Rodegerdts et al., were used for the HSM.
(*123*) (Daniels, S., Nuyts, E., and Wets, G., The Effects of Roundabouts on Traffic Safety for Bicyclists: An Observational Study, *Accident Analysis and Prevention*, 40 (2008), pp. 518-526.)	Before-after study of the effect of injury crashes involving bicycles at 91 roundaboutns in the Flanders area of Belgium. The EB approach was used, but motor vehicle and bicycle volume were not available. Hence safety effects could not be modeled using safety performance functions.	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*124*) De Brabander, B., Nuyts, E., and Vereeck, L., Roadwy safety Effects of Roundabouts in Flanders, *Journal of Safety Research*, 36 (2005), pp. 289-296.	Before-after study of the effect of injury crashes at 95 roundabouts in the Flanders area of Belgium. The EB approach was used but traffic volume was not available and hence safety effects could not be modeled using safety performance functions.	Not added to synthesis. De Brabander and Vereeck (2007) provides updated results from the analysis of the same set of roundabouts.
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities	Added to synthesis only for exhibits of alternative intersection designs. No evidence of quantified safety impacts found.
(*8*) (Persaud, B. N., Retting, R. A., Garder, P. E., and Lord, D., "Observational Before-After Study of the Safety Effect of U.S. Roundabout Conversions Using the Empirical Bayes Method." Transportation Research Record, No. 1751, Washington, D.C., Transportation Research Board, National Research Council, (2001))	Before-after study of the effect on crashes at 23 intersections following change from stop and signal control to roundabout design; seven states, both urban, suburban, and rural	Reference suggested by NCHRP 17-18(4). Added to synthesis. t and s values included in Master Summary table.
(Flannery, A., "Geometric Design and Safety Aspects of Roundabouts." Transportation Research Record, No. 1751, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 76-81.)	Used crash data to identify geometric characteristics of roundabouts that affect safety; MD, FL, and NV	Reference suggested by NCHRP 17-18(4). Briefly reviewed. Did not review in detail since results do not add to findings. Did not add to synthesis.
(Persaud, B. N., Retting, R. A., Garder, P. E., and Lord, D., "Crash Reduction Following Installation of Roundabouts in the United States." Arlington, Va, Insurance Institute for Highway Safety, (2000))	Before and after study of the effect on crashes resulting from the installation of roundabouts; 24 intersections in 8 states; used EB statistics; urban, rural, and suburban	Reference suggested NCHRP 17-18(4). Reference reviewed but not added to synthesis since there is a more recent reference by the authors (Persaud et al., 2001) that presents results from the same research
(Flannery, A. and Elefteriadou, L., "A Review of Roundabout Safety Performance in the United States." Las Vegas, Nev., Proc. 69th Annual Meeting of the Institute of Transportation Engineers , (1999))	Before and after study of the effect on crashes of roundabouts, 3 intersections in FL and 5 in MD	Reference suggested by NCHRP 17-18(4). Did not add to synthesis or review in detail since the studies cited in this reference were reviewed by Elvik and Vaa using meta-analysis and presented in their Handbook.
(Robinson, D. L., "Accidents at Roundabouts in New South Wales." Road and Transport Research, Vol. 7, No. 1, Vermont South, Australia, ARRB Transport Research Ltd., (1998) pp. 3-12.)	Report discusses roundabouts in Australia with special reference to accidents involving bicyclists	Not added to synthesis. More relevant to sections on pedestrian and bicyclist safety.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	Report summarizes a literature review of the relationship between measures of road performance, including safety, and road geometry and condition.	Not added to synthesis. Brief review shoes that the reference has nothing new to add to already substantial results for roundabouts.

DOCUMENT	DESCRIPTION	COMMENT
(Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995), Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))	Review of studies on roundabouts	Reference suggested by NCHRP 17-18(4). Not added to synthesis. Brief review shoes that the reference has nothing new to add to already substantial results for roundabouts. Studies cited already reviewed by Elvik and Vaa in their Handbook.
(Schoon, C. and van Minnen, J., "The Safety of Roundabouts in The Netherlands." Traffic Engineering & Control, Vol. 35, No. 3, London, United Kingdom, Hemming Information Services, (1994) pp. 142-148.)	Before and after study of crashes at 181 intersections in the Netherlands converted to roundabouts	Potential international resource suggested NCHRP 17-18(4). Did not add to synthesis or review in detail since the studies cited in this reference were reviewed by Elvik and Vaa using meta-analysis and presented in their Handbook.
(Corben, B. F., "Crashes at Traffic Signals: Guidelines for a Traffic Engineering Safety Program of Replacing Selected Intersection Signals with Roundabouts." 7, Victoria, Australia, VicRoads and Transport Accident Commission, (1989))	Citation from the Ministry of Transportation of British Columbia library e-catalogue. Study's objective was to develop traffic safety engineering guidelines for when and where to replace existing traffic signals with roundabouts.	Reference suggested by NCHRP 17-18(4). Not added to synthesis. It provided no relevant information for HSM.
(McCoy, P. T. and Malone, M. S., "Safety Effects of Left-Turn Lanes on Urban Four-Lane Roadways." Transportation Research Record 1239, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 17-22.)	Study analyzed accident experience at signalized and unsignalized intersections on urban four-lane highways in Nebraska to assess the safety impacts of implementing left-turn lanes.	Not added to synthesis. More relevant to Approach Roadway Elements section.

From the critical review of references identified, quantitative empirical-based evidence of safety impacts were found for the reduction/elimination of intersection skew angles, the conversion of four-leg or cross intersections into two T-intersections, and for the conversion of intersections into roundabouts. Volume ranges are provided here when available. The safety impacts of other road safety treatments have been described using only qualitative or anecdotal information.

Treatment: Reduce/eliminate intersection skew angle

In research conducted by Harwood et al. (*7*), AMFs for at-grade intersections were estimated by an expert panel from predictive models that were developed in a previous study (*9*) using extended negative binomial regression. Using separate accident prediction models for three- and four-leg intersections the researchers found the following:

- For Total Intersection Accidents at three-leg stop-controlled intersections, AMF = exp(0.0040 SKEW)
- For Total Intersection Accidents at four-leg stop-controlled intersections, AMF = exp(0.0054 SKEW)

where SKEW = intersection skew angle (degrees), expressed as the absolute value of the difference between 90 degrees and the actual intersection angle (*7*). These AMFs are most applicable to rural two-lane and multi-lane intersections.

There was insufficient information to calculate standard error values associated with the Harwood et al. functions.

Harwood et al. added that skew angle is a much less important factor in the operation of signalized intersection than in the operation of stop-controlled intersections. According to Harwood et al., since the traffic signal separates most movements from conflicting approaches, the risk of accidents related to the skew angle between the intersecting approaches is limited at a signalized intersection. Therefore, the AMF for skew angle at four-leg signalized intersections is 1.0 for all cases (*7*). However, given that the safety effect of the skew angle at a signalized intersection is also highly dependent on the operational characteristics of the traffic signal control, logic dictates that the AMF would ultimately depend on the combined effects of the skew angle and the traffic control design elements such as the allowance of right-turns on red signals, and the use of a protected-only phasing for left-turns.

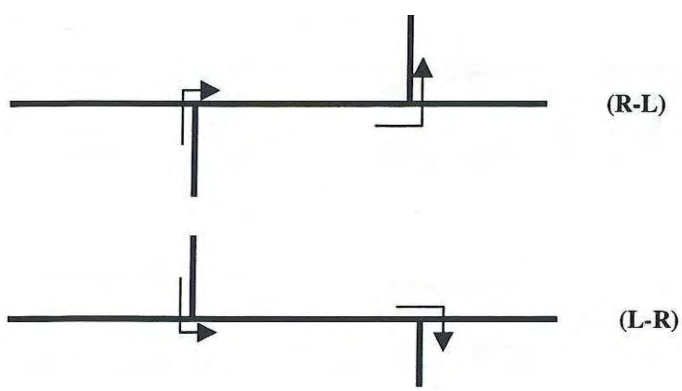
Discussion: Impact of intersection skew angle on drivers

Antonucci et al. stated that roads that intersect with each other at angles less than 90º can present sight distance and operational problems for drivers. As a result, there is likely to be high incidence of right-angle accidents, particularly involving vehicles approaching from the acute angle. Safety issues stemming from intersections with skew angles that are not 90º can be attributed to the fact that vehicles have a longer distance to travel through the intersection (increasing their exposure to conflicts), and drivers (particularly older drivers) may find it difficult to turn their head and neck to view an approach on an acute angle. Furthermore, vehicles turning right at an acute angle may encroach on the lane for vehicles approaching from the opposite direction. When RTOR are permitted, drivers may have more difficulty judging gaps when turning. Also, crossing distances for pedestrians are increased (*4*).

Treatment: Conversion of four-leg or cross intersections into two T-intersections

According to Bared and Kaisar, one of the road safety treatments used at specific sites, where the opportunity exists, to reduce accidents at intersections has been to stagger the intersection or in other words, to convert a cross intersection into a pair of T-intersections (*6*). These staggered intersections can be constructed in one of two ways: left-right staggering and right-left staggering. These two forms of staggering are shown in Exhibit 4-3.

Exhibit 4-3: Basic Forms of Staggered T-Intersections



By applying regression models developed from previous research studies by Vogt et al. (1995) to predict total and injury accidents, Bared and Kaisar calculated the sum of such accidents for two T-intersections and compared these estimates to the predicted accident frequencies for cross intersections (*6*). Using this approach, Bared and Kaisar developed accident reduction functions for rural two-lane by two-lane, and two-lane (minor road) by four-lane (major road) two-way stop-controlled (TWSC) intersections. These functions are shown in Exhibit 4-4 and Exhibit 4-5. For both cases, the authors assumed that the traffic volume on the minor road constituted 10% of the total entering ADT.

Exhibit 4-4: Accident Reduction for Rural 2x2-lane TWSC intersections (6)

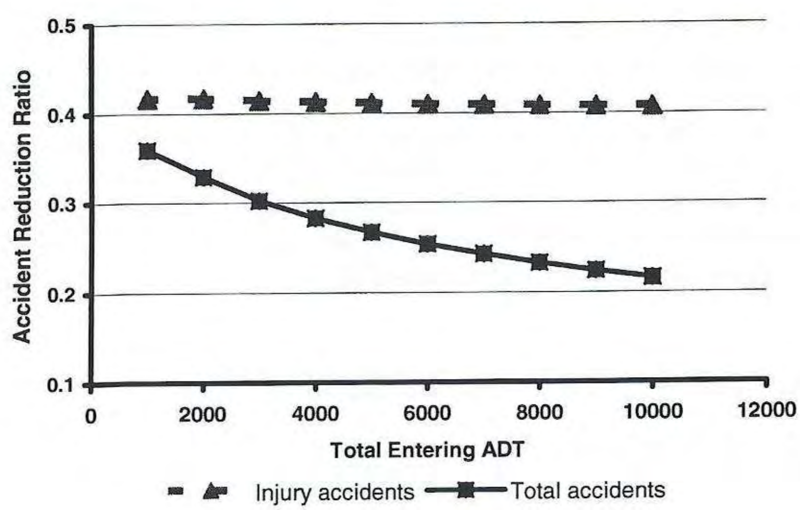
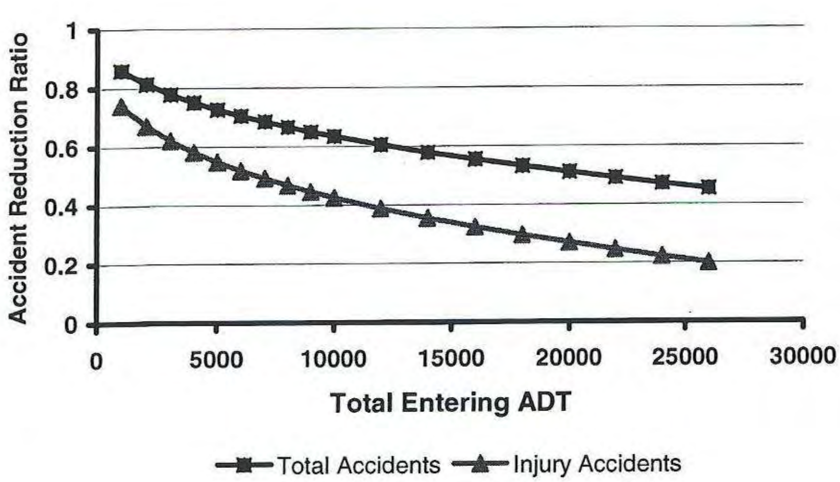


Exhibit 4-5: Accident Reduction for Rural 2x4-lane TWSC intersections (6)



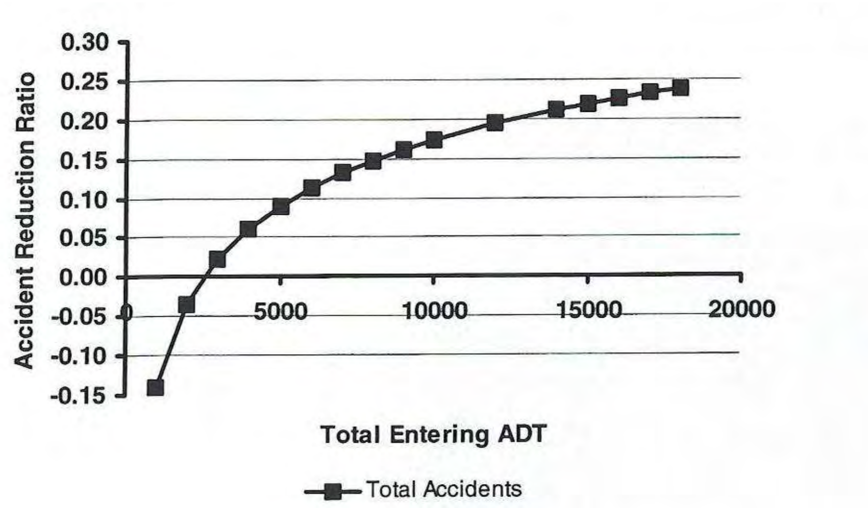
As shown in Exhibit 4-4, the reduction in injury crashes when applying this treatment at rural two-lane by two-lane TWSC intersections is higher (about 40% reduction or an AMF of 0.60) than the reduction in total crashes (between 20% to 35% or AMF value of between 0.8 and 0.65). The authors further noted that the reduction in total crashes resulting from this particular treatment decreases and levels off at approximately 20% (AMF of 0.8) when the total entering ADT flow is 10,000 veh/day.

As shown in Exhibit 4-5, the safety effects of implementing this treatment appeared to be reversed for two-lane (minor road) by four-lane (major road) two-way stop-controlled (TWSC) intersections; reduction in injury crashes is lower (between 20% to 75%, or AMF value of between 0.8 and 0.25) than the reduction in total crashes (between 40% to 85% or AMF value of between 0.6 and 0.15). The reduction in total crashes resulting from this particular treatment decreases and levels off at approximately 20% (AMF of 0.8) for injury crashes and 40% (AMF of 0.6) for total crashes when the total entering ADT flow exceeds 25,000 veh/day. In the application of the models, Bared and Kaisar assumed that four-lane state highways are divided.

There was insufficient information to calculate standard error values for the AMF values developed by Bared and Kaisar.

In addition to the crash reduction functions for unsignalized intersections, Bared and Kaisar also combined the results from regression models developed by Bauer et al. in a previous research study with their own research results to develop crash reduction functions quantifying the safety effects of this particular treatment for signalized intersections (*6*). The large majority of the intersections used in the development of the models included left-turn lanes with fully actuated signals. By assuming a 60% to 40% ratio for traffic volume on the main road versus the crossroad, Bared and Kaisar reported that accident reduction resulting from the road safety treatment increases with increasing traffic volumes and levels off at approximately 25% (AMF of 0.75) beyond total entering ADT volumes of 18,000 veh/day. The results are shown in Exhibit 4-6. Bared and Kaisar reported that the fit of the models was not strong. There was insufficient information to calculate standard error values for the AMF values.

Exhibit 4-6: Accident Reduction for Urban 2x2-lane Signalized intersections



Elvik and Vaa conducted a meta-analysis of a number of studies related to the conversion of cross intersections to two T-intersections and found that the safety effect is dependent on the proportion of minor road traffic at the cross intersection prior to conversion (p. 307) (*5*). According to the authors, it appears that there are no safety benefits when this treatment is applied to cross intersections with little minor road traffic. In fact, the results from the meta-analysis show that both injury and PDO accidents increase. Based on the results of the meta-analysis, Elvik and Vaa also found that the reduction in injury and PDO accidents following the treatment is higher when the proportion of minor road traffic is larger, and that the safety effect is more pronounced for injury accidents. The results from the meta-analysis are summarized in Exhibit 4-7. The traffic volumes at the sites examined were not reported. This study was considered to be of medium-high quality due to the rigorous meta-analysis methodology applied by Elvik and Vaa, and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 4-7: Safety Effectiveness of Converting Cross intersections into two T-intersections

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with little minor road traffic (<15%), traffic volumes Not specified	All types Injury	1.35	0.27
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with some minor road traffic (15-30%), traffic volumes not specified	All types Injury	0.75	0.08
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with heavy minor road traffic (>30%), traffic volumes not specified	All types Injury	0.67	0.10
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with little minor road traffic (<15%), traffic volumes Not specified	All types PDO	1.15	0.11
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with some minor road traffic (15-30%), traffic volumes not specified	All types PDO	1.00	0.09
Elvik and Vaa, 2004	Conversion of cross intersection into two T-intersections	Urban	Intersections with heavy minor road traffic (>30%), traffic volumes not specified	All types PDO	0.90	0.09

Discussion: Conversion of two T-intersections to single 4-leg intersection

None of the studies examined provided any empirically-based evidence of accident reductions resulting from the conversion of two T-intersections to 4-leg intersections. However, according to Antonucci et al., it is expected that this strategy would reduce accidents involving left-turning traffic from the major road onto the cross street at each of the two T intersections, particularly when implemented at signalized offset T-intersections with very high through volumes on the cross street (*4*).

Discussion: Type of T-intersection configuration or staggering

Bared and Kaisar, and Elvik and Vaa noted that the left-right staggering of intersections appear to be more favorable for reducing the number of accidents compared to the right-left configuration. According to Elvik and Vaa, a previous study by Brude and Larsson found that the left-right pattern reduced the number of accidents by 4% while the right-left pattern increased the number of accidents by 7% (*5*). However, the authors added that the differences were not statistically significant.

Treatment: Conversion of intersections into roundabouts

Results from recent studies appear to indicate that converting conventional intersections with stop signs or traffic signals to roundabouts can produce substantial reductions in motor vehicle crashes, particularly injury crashes. Persaud et al. suggest that the crash reductions resulting from the conversion of conventional intersections to roundabouts can be attributed primarily to two factors: reduced traffic speeds, and the elimination or reduction of specific types of motor vehicle conflicts that typically occur at angular intersections (*8*). The conflicts include left-turns against oncoming or opposing traffic, rear end accidents, and right-angle conflicts at both traffic signals and stop signs.

Persaud et al. found that in general, the installation of roundabouts resulted in substantial reductions to crashes (*8*). Using an Empirical Bayesian before-after study approach, the researchers found 40% and 80% reductions in total crashes and injury crashes, respectively, following the implementation of the treatment. The authors analyzed stop-controlled and signalized intersections (prior to conversion), as well as single and multi-lane roundabouts (following conversion) separately, summarized in Exhibit 4-8. This study was ranked medium-high, and an MCF of 1.8 was applied to the standard errors.

Elvik and Vaa conducted a meta-analysis of studies that examined the safety impacts of installing roundabouts and found that the number of property damage only accidents increased following the implementation of the treatments. The researchers found that property damage only accidents increased from 32% to 73%. However, the researchers cautioned that the results were "highly conflicting" and "uncertain" (p. 299) (*5*). These results are not added to the synthesis.

De Brabander and Vereeck used the empirical Bayes before-after study approach to study the impact of roundabouts on injury crashes in the Flanders region of Belgium (*122*). Traffic volume was not available for this evaluation and hence safety effects could not modeled using safety performance functions. Overall, the study estimated a 39% reduction in injury crashes and a 17% reduction in serious injury crashes. Intersections that were previously unsignalized experienced a larger reduction in crashes when roundabouts were introduced compared to intersections that were previously signalized. An MCF of 2.2 was applied to the standard errors from this study.

Rodegerdts et al. provide additional insight with data from 55 intersections in the United States (*120*). This study used the empirical Bayes before-after study approach, included traffic volume data, and was ranked high. An MCF of 1.2 was applied to the standard errors. Results from this study were recommended for the HSM. It is important to note here that many of the same sites that were included in Persaud et al. (*8*) were included in Rodegerdts et al. (*120*) with updated information.

Exhibit 4-8: Safety effectiveness of converting signalized or stop-controlled intersections to roundabouts

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Persaud et al., 2001	Conversion of stop-controlled intersection into single-lane roundabout	Urban	Not specified, AADT = 4,600 - 17,825	All crashes, all severities	0.28	0.108
Persaud et al., 2001	Conversion of stop-controlled intersection into single-lane roundabout	Rural	Not specified, AADT = 7,185 - 17,220	All crashes, all severities	0.42	0.126
Persaud et al., 2001	Conversion of stop-controlled intersection into multi-lane roundabout	Urban	Not specified, AADT = 13,272 - 30,418	All crashes, all severities	0.95	0.180
Persaud et al., 2001	Conversion of signalized intersection into single- or multi-lane roundabout	Urban	Not specified, AADT = 5,322 - 31,525	All crashes, all severities	0.65	0.162
Persaud et al., 2001	Conversion of stop-controlled intersection into single-lane roundabout	Urban	Not specified, AADT = 4,600 - 17,825	All crashes, Injury	0.12	0.144
Persaud et al., 2001	Conversion of stop-controlled intersection into single-lane roundabout	Rural	Not specified, AADT = 7,185 - 17,220	All crashes, Injury	0.18	0.162
Persaud et al., 2001	Conversion of signalized intersection into single- or multi-lane roundabout	Urban	Not specified, AADT = 5,322 - 31,525	All crashes, Injury	0.26	0.252
De Brabander and Vereeck (2007)	Convert to roundabout	Not specified	Not specified	All crashes, injury	0.61	0.079

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
De Brabander and Vereeck (2007)	Convert signalized intersections to roundabout	Not specified	Not specified	All crashes, injury	0.68	0.135
De Brabander and Vereeck (2007)	Convert unsignalized intersection to roundabout	Not specified	Not specified	All crashes, injury	0.56	0.101
De Brabander and Vereeck (2007)	Convert to roundabout	Not specified	Not specified	All crashes, serious injury	0.83	0.230
De Brabander and Vereeck (2007)	Convert signalized intersection to roundabout	Not specified	Not specified	All crashes, serious injury	0.87	0.387
De Brabander and Vereeck (2007)	Convert unsignalized intersection to roundabout	Not specified	Not specified	All crashes, serious injury	0.80	0.297
De Brabander and Vereeck (2007)	Convert to roundabout	Not specified	Not specified	All crashes, light injury	0.62	0.084
De Brabander and Vereeck (2007)	Convert signalized intersection to roundabout	Not specified	Not specified	All crashes, light injury	0.69	0.163
De Brabander and Vereeck (2007)	Convert unsignalized intersection to roundabout	Not specified	Not specified	All crashes, light injury	0.54	0.107
Rodegerdts et al., 2007	Convert signalized intersection to roundabout	Urban All lanes	Unspecified	All types All severities	0.99	0.14
				All types Injury	0.40	0.14
		Suburban Two lanes		All types All severities	0.33	0.05
		All settings All lanes		All types All severities	0.52	0.06
				All types Injury	0.22	0.07
	Convert two-way stop-controlled	All settings All lanes	Unspecified	All types All severities	0.56	0.05

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
	intersection to roundabout			All types Injury	0.18	0.04
		Rural Single-lane		All types All severities	0.29	0.04
				All types Injury	0.13	0.04
		Urban All lanes		All types All severities	0.71	0.11
				All types Injury	0.19	0.10
		Urban Single-lane		All types All severities	0.61	0.12
				All types Injury	0.22	0.12
		Urban Two-lane		All types All severities	0.88	0.21
		Suburban All lanes		All types All severities	0.68	0.08
				All types Injury	0.29	0.10
		Suburban Single-lane		All types All severities	0.22	0.07
				All types Injury	0.22	0.12
		Suburban Two-lane		All types All severities	0.81	0.11
				All types Injury	0.32	0.14
	Convert all-way stop-controlled intersection to roundabout	All settings All lanes		All types All severities	1.03	0.18
Daniels et al. (2008)	Convert to roundabout	Inside built-up areas (urban)	Not specified	Bicyle, injury	1.48	0.516
Daniels et al. (2008)	Convert to roundabout	Inside built-up areas (urban)	Not specified	Bicycle, fatal and serious injury	1.77	1.134
Daniels et al. (2008)	Convert to roundabout	Outside built-up areas (rural)	Not specified	Bicycle, injury	1.01	0.438

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Daniels et al. (2008)	Convert to roundabout	Outside built-up areas (rural)	Not specified	Bicycle, fatal and serious injury	1.21	0.690
Daniels et al. (2008)	Convert to roundabout	Both rural and urban	Not specified	Bicycle, injury	1.27	0.342
Daniels et al. (2008)	Convert to roundabout	Both rural and urban	Not specified	Bicycle, fatal and serious injury	1.44	0.601

Discussion: Impact of roundabouts on pedestrians and bicyclists

The results regarding the impact of roundabouts on pedestrians and bicycles is not consistent. Although there was insufficient data to develop indices of effectiveness for this specific treatment, Persaud et al. (*8*) indicated that single-lane roundabouts appear to be safe for pedestrians and bicyclists as well, on the basis of results from a previous research study in Europe[1]. None of the multi-lane roundabouts examined by the Persaud et al. experienced any pedestrian-related crashes in the "after" period. Elvik and Vaa further added that from a meta-analysis of select studies, results appear to indicate that "pedestrian accidents are reduced to the same extent as other types of accidents when roundabouts are built" and that there is also a reduction in cyclist-related crashes although to a lesser degree (10% to 20% reduction) (*5*). However, Daniels et al. in their before-after empirical Bayes study of 91 locations in Flanders, Belgium, found a 27% increase in total injury crashes involving bicyclists when roundabouts were introduced (*123*) (see Exhibit 4-8). Daniels et al. also found a 44 percent increase in fatal and serious injury crashes involving bicycles following the introduction of roundabouts. However, data on motor vehicle and bicycle traffic were not available for their evaluation. In addition, the study did not indicate the number of single lane and multi-lane roundabouts in their sample. An MCF of 2.2 was applied to the standard errors from this study. Due to the limitations from this study, their results need to be used with caution. It is also important to note that ADA requirements are an important consideration for the safety of pedestrians at roundabouts.

Discussion: Improving deflection of through vehicle travel path

Forced path changes for through-vehicles violate driver expectations and may be difficult for unfamiliar drivers to navigate (*4*). Antonucci et al. speculate that the violation of driver expectancy can often result in reduced speed of the vehicle through the intersection. The researchers further point out that crashes influenced by a deflection in travel path are likely to include rear-end, sideswipe, head-on, and angle. Acceptable deflection angles through intersections (usually ranging from 3^{o} to 5^{o}) vary by individual agency, but are typically related to the design and/or posted speed on an intersection approach. As a result of the high costs of

[1] Hyden, C., and A. Varhelyi. The Effects on Safety, Time Consumption and Environment of Large Scale Use of Roundabouts in an Urban Area: A Case Study. Accident Analysis and Prevention, Vol. 32, 1999, pp. 11-23.

redesigning intersection approaches, the use of pavement markings to delineate the through vehicle path is often used as a countermeasure to the safety problems associated with intersections with deflection angles. However, none of the studies examined provided any empirically-based evidence of accident reductions resulting from the improvements to the deflection on through vehicle travel path at intersections.

Discussion: Providing indirect left-turn

According to Antonucci et al., safety problems associated with left-turns at signalized intersections are magnified at intersections with high traffic volumes, especially those with high volumes of left-turns. Indirect left-turn treatments, such as jughandles before the crossroad, directional median crossovers, and loop roadways beyond the crossroad, can address both safety and operational problems related to left-turns since these treatments remove the left-turning vehicles from the traffic stream without causing them to slow down or stop in a through-traffic lane, and, in turn, reduces the potential for rear-end crashes with through vehicles. Right-angle crashes are also likely to decrease after indirect left turn treatments are implemented, since the turning movement is relocated or changed to a different maneuver (*4*).

Jagannathan et al. compared the safety of 44 New Jersey Jug handle intersections (NJJI) and 50 conventional signalized intersections in New Jersey (*119*). Negative binomial regression models were developed to relate crash frequency with site characteristics including major and minor road AADT, posted speed limit on major and minor road, number of approach lanes in major and minor road and presence/absence of a median. Models were estimated for total accidents, injury and fatal accidents, rear-end accidents, left-turn and angle accidents, and sideswipe accidents. Separate sets of models were developed for conventional and jug handle intersections. The study concluded that for a given level of traffic volume, speed limit, and number of lanes, NJJIs had lower PDO, injury plus fatal accidents, and head-on accidents compared to conventional intersections. The NJJIs also had a higher proportion of rear-end and PDO accidents and a lower proportion of left-turn accidents than conventional intersections. Despite these findings, caution should be exercised in using results from such cross-sectional regression models to infer the safety performance of different entity types. AMFs could not be developed based on the results from this study.

Discussion: Constructing interchange or grade separation

By separating the grades of intersecting roadways, volumes of crossing and turning traffic, as well as the number of vehicle-vehicle conflict points may be reduced. According to Antonucci et al., this can lower the number and severity of crashes caused by these movements and intersection conditions, specifically rear end and angle crashes (*4*). None of the studies examined provided any empirically-based evidence of accident reductions resulting from this particular treatment.

4.1.2. Approach Roadway Elements

In accordance with the Green Book published by AASHTO, an intersection is defined by both its functional and physical areas, as shown in Exhibit 4-9. This functional area not only includes the intersection proper, but also the approaches in which vehicle maneuvers related to the intersection such as lane changing and deceleration take place. As illustrated in Exhibit 4-10, the functional area on the approach to an intersection consists of three basic elements:

- Perception-reaction distance

- Maneuver distance
- Queue-storage distance

The distance traveled during the perception-reaction time will depend upon vehicle speed, driver alertness, and driver familiarity with the location. Where there is a left- or right-turn lane, the maneuver distance includes the length needed for drivers to brake and make lane changes. In the absence of turn lanes, it represents the distance needed to brake and stop comfortably (*2*).

Exhibit 4-9: Physical and Functional Intersection Area (2)

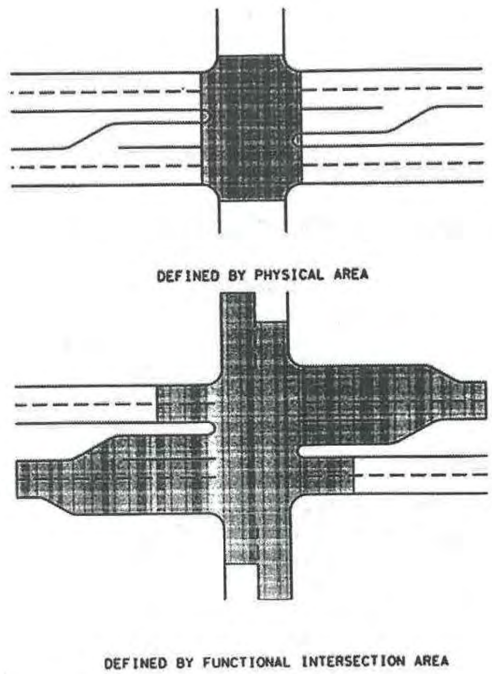
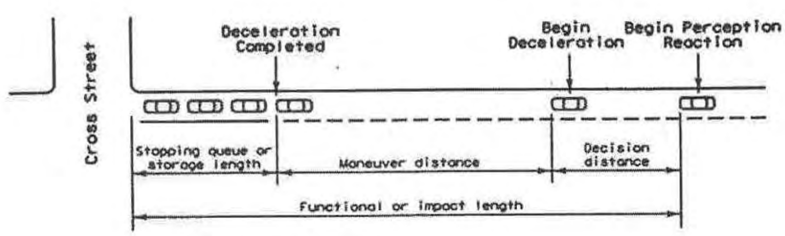


Exhibit 4-10: Elements of the Functional Area of an Intersection (2)



Approach roadway elements considered in the HSM include:

- Lanes
- Shoulders and sidewalks

- Medians

As noted by Neuman et al., reducing the frequency and severity of vehicle-vehicle conflicts can reduce the frequency and severity of intersection crashes. This can be achieved through geometric design improvements such as separating through and turning movements at the intersection, restricting or eliminating turning maneuvers, or providing acceleration lanes (*10*). Higher-cost, longer-term improvements, such as a redesign of the intersection, can also improve safety (*4*). Geometric improvements can provide both operational and safety benefits at intersections. For example, improvements to turning movements, through channelization or separating turns temporally can result in reductions in certain types of crashes. Geometric changes can also improve safety for pedestrians and bicyclists (*4*).

The following sections discuss the safety impact of lanes, shoulders and sidewalks, medians and curbs at both signalized and unsignalized intersections.

4.1.2.1. Lanes

AASHTO defines channelization as "the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement marking to facilitate the orderly movements of both vehicles and pedestrians". Channelization of intersections is typically considered for one or more of the following factors (*2*):

- The paths of vehicles are confined by channelization so that not more than two paths cross at any one point.
- The angle and location at which vehicles merge, diverge, or cross are controlled.
- The amount of paved area is reduced and thereby decreases vehicle wander and narrows the area of conflict between vehicles.
- Clearer indications are provided for the proper path in which movements are to be made.
- The predominant movements are given priority.
- Areas are provided for pedestrian refuge.
- Separate storage lanes permit turning vehicles to wait clear of through-traffic lanes.
- Space is provided for traffic control devices so that they can be more readily perceived.
- Prohibited turns are controlled.
- The speeds of vehicles are restricted to some extent.

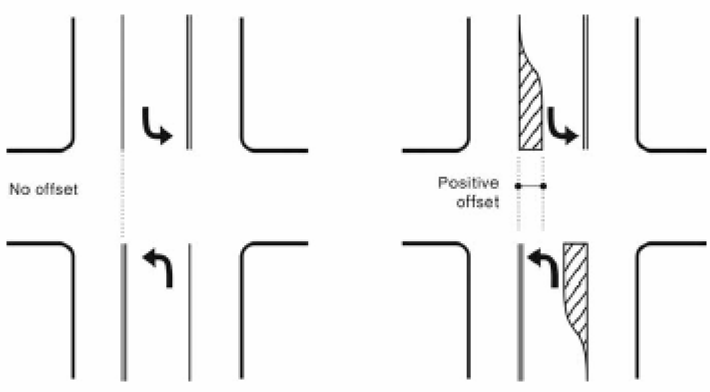
Channelization can be implemented through the use of traffic islands (physical channelization) or road markings (painted channelization) (*5*). Both physical and painted means of channelization are used to demarcate shared and exclusive lanes. As defined in the Highway Capacity Manual, an exclusive turn lane is a designated left-turn or right-turn lane (or lanes) used exclusively by vehicles making those turns (*11*).

According to Antonucci et al., exclusive left-turn lanes are a proven treatment for addressing safety problems associated with left-turning vehicles. By removing left-turning vehicles from the through-traffic stream, conflicts with through vehicles can be reduced or even eliminated depending on the signal timing and phasing scheme. The presence of a left-turn lane allows drivers to wait in the turn lane until there is a gap in opposing traffic through which they can turn safely, and this helps reduce conflicts with opposing through traffic (*4*).

Safety improvements can be made through the proper design of the various elements associated with turn lanes such as the length, width and taper (*4*). For example, the length of a left-turn or right-turn lane should allow for the removal of slow decelerating vehicles from the through traffic stream, thereby reducing the potential for rear-end accidents. This can be particularly important for higher-speed intersections such as those typically found in rural areas. A turn lane that is too short can cause turning queues (especially left-turning vehicles) to spillover into through lanes, forcing through vehicles to stop or change lanes, which can lead to rear-end and sideswipe crashes. In addition, if access to a left-turn lane is blocked, drivers of left-turning vehicles may drive into the opposing lane to reach the left-turn lane; this could result in head-on crashes (*4*).

As discussed by Harwood et al., an emerging issue in the design of left-turn channelization is the restriction in sight distance that opposing left-turn vehicles cause one another (*12*). When opposing left-turn lanes are provided, vehicles waiting to turn left may block the respective driver's view of approaching traffic in the through lanes. This problem may be more acute among older drivers, particularly given that they may experience greater difficulties at intersections as a result of diminished visual capabilities, such as depth and motion perception. These diminished visual capacity traits, often associated with older drivers, can lead to accidents between vehicles turning left from the major road and through vehicles on the opposing major-road approach. As such, an additional key design variable for consideration is the off-set of opposing left-turn lanes. Research findings indicated that an increase in sight distance through positively offsetting left-turn lanes can be beneficial to left-turning drivers, particularly older left-turning drivers (*13*). An illustration of how opposing left-turn lanes can be offset is shown in Exhibit 4-11.

Exhibit 4-11: Offset of Left-turn Lanes (4)



As a result of capacity issues and traffic congestion problems at intersections, many highway agencies use double or even triple left-turn lanes at major intersections. These left-turn configurations, particularly, double left-turn lanes, are attractive design alternatives because they generally increase the overall capacity at an intersection by reducing the required left-turn green time. While dual left-turn lanes are normally used in tandem with protected left-turn phasing, some jurisdictions have opted to employ protected-plus-permitted left-turn signal phasing to further increase intersection capacities (*14*). However, there are a number of potential problems with permissive double left-turn movements. These concerns include reduced sight distances, potential increases in sideswipe accidents, and also impaired ability for left-turning drivers to judge gaps in conflicting traffic (*15*). Signal phasing is discussed in Section 4.2.

The reader is directed to AASHTO's Policy on Geometric Design for Highways and Streets (*2*), the TRB Highway Capacity Manual (*11*), NCHRP Report 279 (*16*), the FHWA's MUTCD (*17*), and the policies of individual highway agencies for further information on the design criteria for turn lanes.

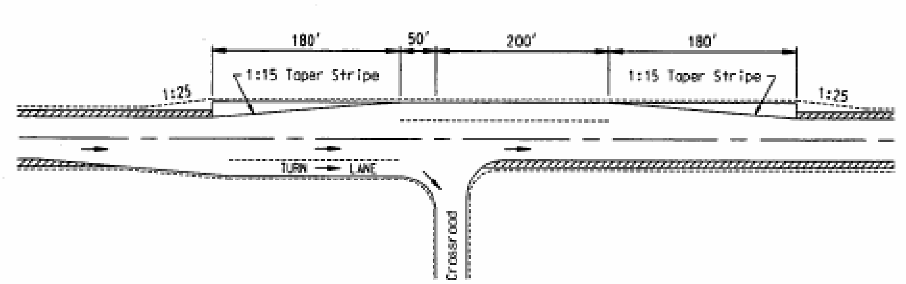
This section discusses the safety effects of the presence (or absence) of left-turn lanes and right-turn lanes as well as the different design elements associated with lanes at intersections in general. The safety effect of the number of lanes on an intersection approach is not addressed here because this is a variable that is primarily determined by traffic demand and the desired level of service. Harwood noted that with a demand-related design parameter such as the number of lanes, it is difficult to directly assess whether any observed safety effects are due to the number of lanes or due to the traffic volume on the approach (*18*).

This edition of the HSM addresses the safety effect of adding left-turn lanes, median acceleration lanes, and by-pass lanes, as well as the elements used to channelize left-turn movements such as bollards, medians, or pavement markings. The HSM will attempt to address the design parameters related to left-turn and right-turn lanes such as the length and offset, along with other related issues such as the use of dual and triple left-turn lanes, dual right-turn lanes, and by-pass lanes.

The reader is directed to the "Intersection Channelization Design Guide" for additional information on commonly-used channelization treatments and practices (*16*). Given that the safety at intersections is closely related to the type of traffic control as well, the reader is also referred to Section 4.2 of the HSM.

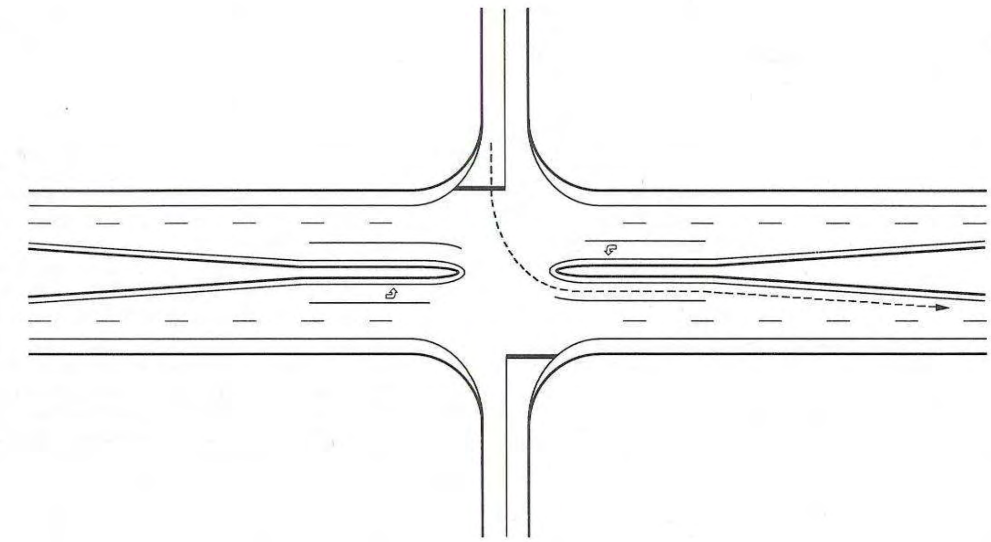
When a left-turn lane is not warranted, or if the construction of a left-turn lane is not practical due to a number of reasons (such as a limited right-of-way, terrain, etc.), highway designers sometimes construct left-turn bypass lanes as an alternative or short-term solution at intersections with slower-speed, lower volume traffic (*19*). By-pass lanes are more often constructed on three-leg or T-intersections than on four-leg intersections because there tends to be lower traffic volumes at the three-leg intersections and because there are no streets on the opposite side to the minor street approach, the by-pass lane can be constructed with no conflicting traffic. The objective of the by-pass lane at a three-leg or T-intersection is to allow for a vehicle on the major road to move around or pass a stopped or decelerating vehicle traveling in the same direction and making a left-turn onto the minor street (*20*). An example of a left-turn by-pass lane is illustrated in Exhibit 4-12.

Exhibit 4-12: Left-Turn By-Pass Lanes at T-intersections (19)



Another left-turn treatment that is discussed in this section is median left-turn lanes. These lanes have been used by a number of highway agencies at divided highway intersections to allow vehicles turning left onto a divided highway to continue through the median roadway without stopping and merge into traffic on the far side of the divided highway (*21*). An example of a median left-turn acceleration lane is shown in Exhibit 4-13.

Exhibit 4-13: Median Left-turn Acceleration Lane on Divided Highway Intersections (21)



The provision of exclusive right-turn lanes can minimize accidents between vehicles turning right and following vehicles, particularly at high-volume and high-speed intersections of major roads. However, it is possible that the installation of a right-turn lane could create other safety problems at the intersection. For example, as shown in Exhibit 4-14, a vehicle on a right-turn lane can obscure the sight of the driver of a following through vehicle who is trying to detect vehicles on the cross streets and vice versa (*5*). This can lead to accidents between vehicles turning left, turning right, or crossing from the minor road and through vehicles on the major road. According to Neuman et al., these types of accidents can potentially be reduced by offsetting right-turn lanes, as shown in Exhibit 4-15.

Exhibit 4-14: Blind spot created by right-turn lanes at intersections (5)

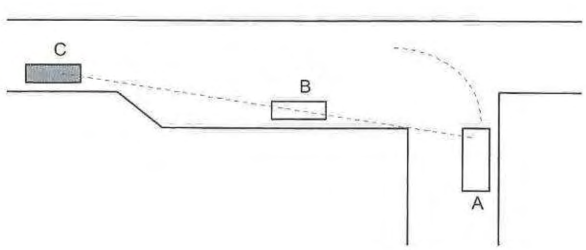
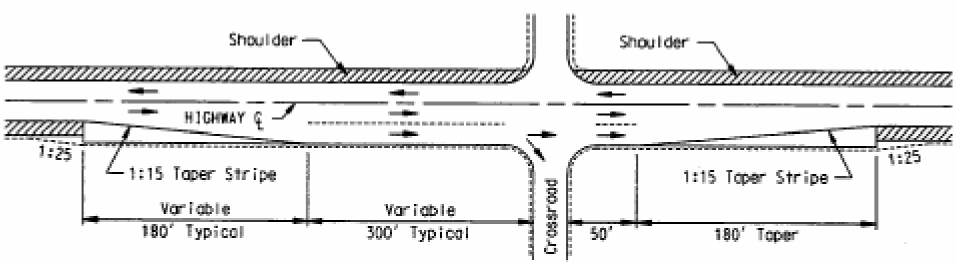


Exhibit 4-15: Offset Right-turn Lanes (16)

As noted earlier, bypass lanes at four-leg/cross intersections should are typically used only when all other solutions have been deemed impractical and where the cross street traffic volume is low. The typical configuration of by-pass lanes at four-leg intersections is usually comprised of a combined right-turn/by-pass lane on the right side of the through lane as shown in Exhibit 4-16. With the presence of the minor road approaches on both sides of a four-leg intersection, the number of conflict points are increased and there is greater concern for safety resulting from the implementation of by-pass lanes four-leg/cross intersections (*20*).

Exhibit 4-16: Combined By-Pass and Right-turn Lanes (19)



Auxiliary through lanes are typically used at intersections to increase the capacity of through traffic. The safety effect of auxiliary through lanes, as well as the different design parameters related to these types of lanes may be addressed in a future edition of the Highway Safety Manual.

Exhibit 4-17: Resources examined to investigate the safety effect of lanes at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*125*) Wang, X. and Abdel-Aty, M., Right-Angle Crash Ocurrence at Signalized Intersections, *Transportation Research Record* 2019, (2007), pp. 156-168.	Negative binomial regression models were estimated relating the frequency of right angle crashes with many intersection and approach characteristics including whether there a positive left-turn offset on the crossing roadway (instead of negative offset)	Added to synthesis.
(*126*) Jonsson, T., Ivan, J.N., and Zhang, C., Crash Prediction Models for Intersections on Rural Multilane Highways: Differences by Collision Type, Transportation Research Record 2019, (2007), pp. 91-98	Negative binomial regression models were estimated relating the frequency of different types of crashes on stop controlled intersections on rural multilane roads with many intersection and approach characteristics. Independent variables include many site characteristics including whether there was left turn channelization	Added to synthesis. AMFs with t statistics are provided.
(*127*) Fitzpatrick, K., Schneider IV, W.H., and Park, E.S., Operation and Safety of Right-Turn Lane Designs, *Transportation Research Record* 1961, (2006), pp. 55-64.	This study compiled crash data from five sites in Irving and four sites from College Station, Texas. The intent was to look at the number of right-turn crashes associated with four types of right turn treatments: Right-turn lane with lane line, Right-turn lane with island, Shared through-right lane, and Shared through-right lane with island.	Not added to synthesis. There were only 16 right turn crashes that occurred in the sample of sites used in this study. Does not add much to the safety knowledge.
(*128*) Wang, X., Abdel-Aty, M., and Brady, P., Crash Estimation at Signalized Intersections: Significant Factors and Temporal Effect, *Transportation Research Record* 1953, (2006), pp. 10-20	Negative binomial regression models were estimated relating the frequency of crashes with many intersection and approach characteristics including the presence of exclusive right-turn lanes.	Not added to synthesis. Other studies of the same treatment (e.g., Harwood et al., 2002) have used a more defensible approach to determine the safety effect of right-turn lanes.
(*129*) Wang, X. and Abdel-Aty, M., Temporal and Spatial Analysis of Rear-end Crashes at Signalized Intersections, *Accident Analysis and Prevention*, 38 (2006), pp. 1137-1150.	Negative binomial regression models were estimated relating the frequency of rear-end crashes with many intersection and approach characteristics including the presence of exclusive right-turn and left-turn lanes.	Not added to synthesis. Other studies of the same treatment (e.g., Harwood et al., 2002) have used a more defensible approach to determine the safety effect of right-turn and left-turn lanes.
(*130*) Abdel-Aty, M. and Wang, X., Crash Estimation at Signalized Intersections Along Corridors: Analyzing Spatial Effect and Identifying Significant Factors, *Transportation Research Record* 1953 (2006), pp. 98-111.	Negative binomial regression models were estimated relating the frequency of crashes with many intersection and approach characteristics including the presence of exclusive right-turn lanes.	Not added to synthesis. Other studies of the same treatment (e.g., Harwood et al., 2002) have used a more defensible approach to determine the safety effect of right-turn lanes.

DOCUMENT	DESCRIPTION	COMMENT
(*131*) Kim, D. and Washington, S., The Significance of Endogeneity Problems in Crash Models: An Examination of Left-Turn Lanes in Intersection Crash Models, *Accident Analysis and Prevention*, 38 (2006), pp. 1094-1100.	Regression models were estimated to relating angle crashes to the intersection characteristics including left-turn lanes. A limited information maximum likelihood (LIML) approach was used to account for the endogeneity between left-turn lane presence and angle crashes.	Not added to synthesis. Other studies of the same treatment (e.g., Harwood et al., 2002) have used a more defensible approach to determine the safety effect of left-turn lanes.
Lee, Jae-Joon.; Hummer , E, Joseph.; Rouphail, M. Nagui. False Capacity for Lane Drops. North Carolina State University, Research and Analysis Group, Final Report: Project HWY-2003-07. 2005.	This paper developed regression models to explain lane utilization for six defined intersection types in North Carolina using 94 sites. This paper also looked at how land drop affects safety. 3 years of collision data and collision rates. The authors looked at patterns in the collision rates for a few types of lanes drops.	No safety effect estimated. Not added to synthesis.
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis. Results from meta-analysis (p. 293) used to calculate t and s values.
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities. Only presents results from select previous research studies.	Added to synthesis. Only descriptive information about lanes added. The only quantitative information found (AMFs developed by Harwood et al, 2002) not added since the study cited will be reviewed first-hand.
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Reference discusses potential safety impacts of reducing intersection skew and providing left-turn lanes with positive offsets for older drivers	Not added to synthesis. No AMFs or other quantified evidence of safety improvements.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	Interim report for study designed to develop a methodology to predict the safety performance of various elements such as Lane width, Shoulder width and curbs, etc. on urban and suburban arterials.	Results not available.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Study reviews and brings together the best available evidence on the safety impact of traffic operations. All the studies reviewed report on crash occurrence, severity or proven crash surrogates.	Not added to synthesis because reference does not provide sufficient information from studies cited needed to properly assess the soundness of the approach, and the details related each of those studies. In addition, the majority of the studies cited has been or will be reviewed first-hand.

DOCUMENT	DESCRIPTION	COMMENT
(*12*) (Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Rabbani, E. R., Hauer, E., Elefteriadou, L., and Griffith, M. S., "Safety Effectiveness of Intersection Left- and Right-Turn Lanes." Washington, D.C., 82nd Transportation Research Board Annual Meeting, (2003))	Conducted a well designed before and after with control study of adding left-turns lanes, adding right-turn lanes, or extending the length of the lanes at intersections	Suggested by NCHRP 17-18(4). Added to synthesis. AMFs were developed along with standard error values for addition of left- and right-turn lanes at T- and four-leg intersections with varying traffic controls.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Reference discusses issues associated with aggressive driving and potential strategies to mitigate the problem.	Not added to synthesis. Brief mention about possibly providing longer left-turn lanes to minimize driver frustration (therefore discouraging aggressive driving behavior). Overall, material not relevant to the HSM.
(*10*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Report is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections	Added to synthesis. Only discussion on offset right-turn lanes, left-and right-turn acceleration lanes added. Reference cites two studies by Harwood et al. (2002) that have been reviewed first-hand and added to synthesis.
(*22*) (Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Kohlman Rabbani,E.R., Hauer, E., Elefteriadou, L., "Safety Effectiveness of Intersection Left- and Right-Turn Lanes" Federal Highway Administration FHWA-RD-02-089, McLean, Va. (2002))	Same study as (*12*)	Added to synthesis.
(Strathman, J. G., Duecker, K. J., Zang, J., and Williams, T., "Analysis of Design Attributes and Crashes on Oregon Highway System." FHWA-OR-RD-02-01, Washington, D.C., Federal Highway Administration, (2001))	Study developed crash frequency models and crash reduction factors for freeway and non-freeway road segments.	Not added to synthesis due to shortcomings in study approach. Study attempted to relate changes in crashes with treatments such as the presence of turn lanes but removed intersection crashes from database. In addition, some road segments had continuous two-way left-turn lanes, which mean that the safety effects are really due to a combination of treatments and cannot just be attributed to turn lanes alone.
(Thomas, G. B. and Smith, D. J., "Effectiveness of Roadway Safety Improvements." Ames, Iowa Department of Transportation, (2001))	Analyzes seven intersection improvement categories in the State of Kansas including new signals, new signals and turn lanes, add turn phasing to existing signal, add turn phasing and turn lane to existing signals, replace pedestal mount signals with mast arm mounted signals, add turn lanes only and other geometric improvements.	Not added to synthesis. Findings from this naïve before-after study have been superseded by findings from more recent studies (Harwood et al., 2004) that have used more defensible methods (eg. EB approach).

DOCUMENT	DESCRIPTION	COMMENT
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Study presents an algorithm for predicting the safety performance of various factors for roadway segments and for at-grade intersections on rural two-lane highways	Not added to synthesis. Findings from this expert panel have been superseded with findings from a more recent study by the same principle researchers (Harwood et al., 2004)
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Study investigated low-cost safety and operational improvements for two-lane and three-lane roadways.	Not added to synthesis. Some anecdotal evidence of safety impacts resulting from left-turn channelization but insufficient information to properly assess the validity of findings or to calculate t and s values.
(Dixon, K. K., Hibbard, J. L., and Nyman, H., "Right-Turn Treatment for Signalized Intersections." Dallas, Tex., Urban Street Symposium Conference Proceedings, (1999))	Study of right-turn strategies; comparative analysis of two-years of crash history at select intersections in Atlanta	Suggested by NCHRP 17-18(4). Not added to synthesis. Study is a cross-sectional study that did not account for confounding factors. In addition, there are several stronger studies on right-turn lanes already included in synthesis [see (Harwood et al., 2003) and (Harwood et al., 2000)]
(Vogt, A., "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized." FHWA-RD-99-128, McLean, Va., Federal Highway Administration, (1999))	Analyzed the relationship between crashes and intersection elements (including channelization) at 3 types of rural intersections in CA and MI	Suggested by NCHRP 17-18(4). Not added to synthesis. Finding from this study already used as part of effort by expert panel to develop AMFs in study by Harwood et al. (2000).
(*20*) (Preston, H. and Schoenecker, T., "Bypass Lane Safety, Operations, and Design Study." MN/RC - 2000-22, St.Paul, Minnesota Department of Transportation, (1999))	Naïve before and after analysis of bypass lanes affect on crashes in rural Minnesota	Suggested by NCHRP 17-18(4). Added to synthesis. Used crash data in reference (see Figure 5.23 on p. 72) to calculate t and s values.
(*14*) (Tarrall, M. B. and Dixon, K. K., "Conflict Analysis for Double Left-Turn Lanes with Protected-Plus-Permitted Signal Phases." Transportation Research Record 1635, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 1-19.)	Used traffic conflicts to assess the safety effect of three double-left-turn lanes with protected-plus-permitted phasing, metro Atlanta	Suggested by NCHRP 17-18(4). Qualitative information added to synthesis. No quantitative information on safety impacts added because study uses conflicts, not accidents. In addition, study is cross-section study but does not discuss potential effects of confounding factors and whether direct comparisons of conflict rates can be made.
(Staplin, L., Harkey, D. L., Lococo, K. H., and Tarawneh, M. S., "Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians Volume: I: Final Report." FHWA-RD-96-132, McLean, Va., Federal Highway Administration, (1997))	Study presents findings of changing geometric and operational characteristics and measuring the impact on older drivers through human factors measures.	Not added to synthesis. Some discussion about safety issues related to offset left-turn lanes and right-turn curb radius on older drivers. However, these discussions have already been added to synthesis using material from other studies previously reviewed. No quantitative information on safety effects of these treatments was presented.

DOCUMENT	DESCRIPTION	COMMENT
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Reference reviewed existing research and provided guidelines on highway engineering improvements that would help older drivers and pedestrians.	Not added to synthesis. No AMFs or other quantitative evidence of safety impacts found.
(*15*) (Carnahan, C. R., Fox, W. C., French, K. A., Hange, W. A., Henderson, J. L., Hook, D. J. P., Imansepahi, A., Khattak, S. S., Paulson, J. D., Resseguie, J. K., Richey, J. M., and Searls, T. D., "Permissive Double Left Turns: Are They Safe?" Washington, D.C., ITE 1995 Compendium of Technical Papers, (1995) pp. 214-218.)	Comparison of crash rates at signals with single and double left-turns operating with permissive and protect-only phasing in Denver and Colorado Springs metro areas	Suggested by NCHRP 17-18(4). Insufficient data to determine t and s values. In addition, comparison of accident rates, not frequencies but insufficient information about exposure to properly assess if comparison of accident rates is feasible. Qualitative information added to synthesis.
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Report is a detailed study of the operational and safety considerations of median widths.	Only figure of median acceleration lane added. No quantitative information found, only discussions and anecdotal evidence presented.
(Maze, T. H., Henderson, J. L., and Sankar, R., "Impacts on Safety of Left-Turn Treatment at High Speed Signalized Intersections." HR-347, Ames, Iowa Highway Research Board, (1994))	Study investigated the safety effects of left-turn treatment at high speed signalized intersections and developed regression models to estimate accident rates for left-turn and total approach accidents	Not added to synthesis. Results from more recent studies [(Harwood et al., 2002)] using stronger methodologies have already been incorporated into synthesis.
(Kuciemba, S. R. and Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume V - Intersections." FHWA-RD-91-048, Washington, D.C., Federal Highway Administration, (1992))	Report briefly discusses nine studies (1972 to 1988) that examined the relationship between intersections and safety.	Not added to synthesis. Only anecdotal evidence and discussions are presented. No quantitative information found.
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)	Analyzed the relationship between crashes and intersection elements (including channelization) at high-speed intersections in CA	Suggested by NCHRP 17-18(4). Not added to synthesis. Study correlated approach accident rates with different types of left-turn signal phasing rather than the absence or presence of left-turn lanes. More relevant to intersection operations.
(McCoy, P. T. and Malone, M. S., "Safety Effects of Left-Turn Lanes on Urban Four-Lane Roadways." Transportation Research Record 1239, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 17-22.)	Used crash data at signalized and unsignalized intersections in NE to determine the effect of left-turn lanes on safety	Suggested by NCHRP 17-18(4). Not added to synthesis. Finding from this study already used as part of effort by expert panel to develop AMFs in study by Harwood et al. (2000).

DOCUMENT	DESCRIPTION	COMMENT
(Neuman, T. R., "NCHRP Report 279: Intersection Channelization Design Guide." Washington, D.C., Transportation Research Board, National Research Council, (1985))	Additional information on factors to consider for constructing right-turn lanes or for *design* guidelines (e.g., taper length, storage lane length, and corner radius design guidelines) for right-turn lanes. The report also addresses multiple turn lanes.	Not added to synthesis although reference is one of the studies reader is directed to for more information. Discussion and anecdotal evidence presented for many design parameters associated with left- and right-turn lanes. These discussions already added from more recent references. No quantitative information found.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Report is a synthesis of 17 safety research areas, including channelization and left-turn lanes.	Not added to synthesis. Mostly anecdotal and qualitative information provided, all of which have already been added to synthesis from more recent references.
(Box, P. C., "Intersections." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 4, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Study summarizes finds from a number of studies (prior to 1970) that investigated the various design and operational parameters of intersections.	Not added to synthesis. Study included brief discussion on findings from early studies that investigated left-turn treatments. However, these findings have since been superseded by more results from more recent studies.

The effectiveness of a number of left-turn and right-turn treatments has been quantified for two-lane and multi-lane rural highways, as well as urban and suburban arterials.

Treatment: Add left-turn lanes to major road approaches at intersections

Elvik and Vaa conducted a meta-analysis of a number of studies related to the addition of left-turn lanes through the use of physical and painted channelization treatments, and found that the use of physical means of channelization (e.g., using traffic islands) resulted in decreases in injury accidents and mixed results in PDO accidents. Conversely, the authors found that adding painted left-turn lanes produced mixed results in injury accidents and decreases in PDO accidents (p. 293) (*5*). A distinction was made in terms of the types of intersections (T-intersections versus four-leg or cross intersections).The majority of the sites examined were two-lane roads with traffic volumes ranging from 5,000 veh/day to 15,000 veh/day. The results from the meta-analysis are summarized in Exhibit 4-18 to Exhibit 4-19. This study was considered to be of medium-high quality due to the rigorous methodology applied by Elvik and Vaa, and the standard error values have been multiplied with a method correction factor of 1.8 to compensate for this.

Harwood et al. (2002) investigated the safety effectiveness of adding left-turn lanes with a before-after study using a combination of three approaches: the yoked comparison (YC) or matched-pair approach, the comparison group approach (CG), and the Empirical Bayes (EB) approach (*22*). In descending order of appropriateness, results from the EB approach were deemed to be the most credible followed by the results from the CG approach and then the YC approach. For cases where the EB result was not statistically significant but the CG or YC result was statistically significant, the result from CG or YC approach was adopted as the final result (*22*). The intersections studied were located in both urban and rural areas, and were either traffic signal controlled or two-way stop-controlled. For the sites examined, traffic volumes had a range of 1,600 veh/day to 55,100 veh/day for major road ADT, 25 veh/day to 26,000 veh/day for minor road ADT, and 1,100 veh/day to 62,300 veh/day for total entering ADT. The results from the study quantifying the safety effect of adding a left-turn lane on a single major road approach at T-intersections are shown in Exhibit 4-18. The safety impact of adding a left-turn lane on a single major road approach is summarized in Exhibit 4-19. The safety impact of adding left-turn lanes on both major road approaches at four-leg/cross intersections is summarized in Exhibit 4-20. These results were assigned a high rating; a MCF of 1.2 was applied to the s ideal calculated using reported standard error values.

Standard error values are not available for some AMFs because those values were developed based on the judgment of an expert panel using a number of previous research studies for rural two-lane roads, reported by Harwood et al. (2000) (*7*). Despite the lack of standard error values, these results were determined to be the best available knowledge at this time and suggested by Harwood et al. (2002) (*22*).

Exhibit 4-18: Safety effectiveness of adding left-turn lanes at T-intersections

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Physical channelization of left-turn lane on major road	Mostly rural	T-intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, Injury	0.73	0.23
Elvik and Vaa, 2004	Physical channelization of left-turn lane on major road	Mostly rural	T-intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, PDO	1.20	0.42
Elvik and Vaa, 2004	Painted channelization of left-turn lane on major road	Mostly rural	T-intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, Injury	0.78	0.25
Elvik and Vaa, 2004	Painted channelization of left-turn lane on major road	Mostly rural	T-intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, PDO	0.80	0.34
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Stop-controlled T-intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, all severities	0.56	0.07
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Stop-controlled T-intersections, Major road 1,520 to 40,600 vpd, Minor road 200 to 8000 vpd	All types, all severities	0.67	0.15
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Stop-controlled T-intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, Fatal and Injury	0.45	0.10

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Signal controlled T-intersections, volume not reported	All types, all severities	0.85	n/a
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Signal controlled T-intersections, volume not reported	All types, all severities	0.93	n/a
Harkey et al., (2008)	Installation of left-turn lane on single major road approach	Urban	Stop-controlled T-intersections, volume not reported	All types, Fatal and Injury	0.65	n/a
Harkey et al., (2008)	Installation of left-turn lane on single major road approach	Urban	Signal controlled T-intersections, volume not reported	All types, Fatal and Injury	0.94	n/a

Exhibit 4-19: Safety effectiveness of adding left-turn lanes on single major road approach at four-leg/cross intersections

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Physical channelization of left-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, Injury	0.96	0.21
Elvik and Vaa, 2004	Physical channelization of left-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, PDO	0.84	0.39
Elvik and Vaa, 2004	Painted channelization of left-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, Injury	1.28	0.48
Elvik and Vaa, 2004	Painted channelization of left-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, PDO	0.74	0.22

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Stop-controlled four-leg/cross intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, all severities	0.72	0.03
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Stop-controlled four-leg/cross intersections, Major road 1,520 to 40,600 vpd, Minor road 200 to 8000 vpd	All types, all severities	0.73	0.04
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Signal controlled four-leg/cross intersections, volume not reported	All types, all severities	0.82	n/a
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Signal controlled four-leg/cross intersections, Major road 7,200 to 55,100 vpd, Minor road 550 to 2,600 vpd	All types, all severities	0.90	0.10
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Newly signalized four-leg/cross intersections, Major road 4,600 to 40,300 vpd, Minor road 100 to 13,700 vpd	All types, all severities	0.76	0.03
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Rural	Stop-controlled four-leg/cross intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, Fatal and Injury	0.65	0.04
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Stop-controlled four-leg/cross intersections, Major road 1,520 to 40,600 vpd, Minor road 200 to 8000 vpd	All types, Fatal and Injury	0.71	0.05
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Signal controlled four-leg/cross intersections, Major road 7,200 to 55,100 vpd, Minor road 550 to 2,600 vpd	All types, Fatal and Injury	0.91	0.02

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of left-turn lane on single major road approach	Urban	Newly signalized four-leg/cross intersections, Major road 4,600 to 40,300 vpd, Minor road 100 to 13,700 vpd	All types, Fatal and Injury	0.72	0.06

Exhibit 4-20: Safety effectiveness of adding left-turn lanes on both major road approaches at four-leg/cross intersections

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Rural	Stop-controlled four-leg/cross intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, all severities	0.52	0.04
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Stop-controlled four-leg/cross intersections, Major road 1,520 to 40,600 vpd, Minor road 200 to 8000 vpd	All types, all severities	0.53	0.04
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Rural	Traffic Signal controlled four-leg/cross intersections, volume not reported	All types, all severities	0.67	n/a
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Traffic signal controlled four-leg/cross intersections, Major road 7,200 to 55,100 vpd, Minor road 550 to 2,600 vpd	All types, all severities	0.81	0.13
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Newly signalized four-leg/cross intersections, Major road 4,600 to 40,300 vpd, Minor road 100 to 13,700 vpd	All types, all severities	0.58	0.04
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Rural	Stop-controlled four-leg/cross intersections, Major road 1,600 to 32,400 vpd, Minor road 50 to 11,800 vpd	All types, Fatal and Injury	0.42	0.04

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Stop-controlled four-leg/cross intersections, Major road 1,520 to 40,600 vpd, Minor road 200 to 8000 vpd	All types, Fatal and Injury	0.50	0.06
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Traffic signal controlled four-leg/cross intersections, Major road 7,200 to 55,100 vpd, Minor road 550 to 2,600 vpd	All types, Fatal and Injury	0.83	0.02
Harwood et al., 2002	Installation of left-turn lanes on both major road approaches	Urban	Newly signalized four-leg/cross intersections, Major road 4,600 to 40,300 vpd, Minor road 100 to 13,700 vpd	All types, Fatal and Injury	0.52	0.07

Discussion: Provide positive offset for left-turn lanes

According to Antonucci et al., it is likely that providing positive offset for left-turn lanes helps to reduce the potential for left-turning crashes at signalized intersections since it provides the opportunity for longer sight distances for the benefit of left-turning drivers to spot oncoming vehicles thereby improving their ability to discern appropriate gaps in opposing through traffic (*4*). However, there is only limited empirically-based evidence of such an effect. Wang and Abdel-Aty developed regression models relating right-angle crash frequency with intersection and approach characteristics at 197 four-leg signalized intersections in Central Florida (*125*). Models were developed at the intersection level, roadway level, and approach level. In the roadway and approach level models, crashes were either assigned to the at-fault vehicle or with the roadway or approach whose stop line was closest to the crash location (defined as near-side). Some of their models indicated that the presence of zero or positive left-turn offset on the crossing roadway (compared to having negative offset) is associated with fewer right-angle crashes.

Jonsson et al. (*126*) developed regression models relating single vehicle, intersection direction (angle), opposite direction, some direction, and total crashes, with intersection characteristics at stop controlled T and cross intersections on rural multilane roads in California. Their models showed that for four-leg intersections, the presence of left-turn channelization (raised/curb or painted) seems to reduce same direction and total crashes.

AMFs and standard errors from these two studies are provided in Exhibit 4-21 (a method correction factor of 2.0 was applied to the standard errors from both these studies). As part of Phase 2 of FHWA's low cost pooled fund effort, a study is being conducting to evaluate the safety impact of positive offset for left-turn lanes at signalized intersections. This study is using the before-after empirical Bayes study design. The results of this evaluation are expected to be available in Fall 2008.

Exhibit 4-21: Safety effectiveness of introducing left-turn offset

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Wang and Abdel-Aty, 2007	Introducing zero or positive offset left-turn lane on crossing roadway	Urban	Signalized intersection (roadway-level at-fault model); Major road through AADT 30.607 to 82,774	Right angle, all severities	0.739	0.256
Wang and Abdel-Aty, 2007	Introducing zero or positive offset left-turn lane on crossing roadway	Urban	Signalized intersection (approach-level at-fault model); Major road through AADT 30.607 to 82,774	Right angle, all severities	0.801	0.275
Jonsson et al. 2007	Introduce raised/curb left-turn channelization	Rural	Four-leg stop controlled intersections on multilane roads	Same direction crashes, all severities	0.749	0.270
Jonsson et al. 2007	Introduce raised/curb left-turn channelization	Rural	Four-leg stop controlled intersections on multilane roads	Total crashes, all severities	0.872	0.281
Jonsson et al. 2007	Introduce painted left-turn channelization	Rural	Four-leg stop controlled intersections on multilane roads	Same direction crashes, all severities	0.613	0.189
Jonsson et al. 2007	Introduce painted left-turn channelization	Rural	Four-leg stop controlled intersections on multilane roads	Total crashes, all severities	0.671	0.175

Discussion: Provide left-turn acceleration lanes at divided highway intersections

By removing the slower left-turning vehicles from through lanes, this treatment is expected to reduce rear-end and sideswipe accidents resulting from conflicts between vehicles turning left onto the highway and through vehicles on the highway (*10*). However, no quantitative estimates of the safety effectiveness of this treatment are available. Neuman et al. identified three potential areas of concern with regards to the use of left-turn acceleration lanes at divided highway intersections. First, the length of the lanes is critical since excessively long acceleration lanes may be mistaken as an additional through lane, resulting in additional conflicts due to last-minute lane changes; second, the appropriate design of the median opening area is also a key design parameter in minimizing conflicts between vehicles entering the left-turn acceleration lane and other through and turning vehicles using the median opening; third, the installation of left-turn acceleration lanes increases the overall width of the intersection, and this in turn may cause potential problems for pedestrians crossing the intersection (*10*).

Treatment: Add right-turn lanes to major road approaches at intersections

Elvik and Vaa carried out a meta-analysis of a number of studies that examined the safety effects of adding right-turn lanes using physical channelization treatments (e.g. using traffic islands), and found that the use of this particular type of treatment resulted in decreases in both injury accidents and PDO accidents (p. 293) (*5*). As with left-turn lanes, a distinction was made in terms of the types of intersections (T-intersections versus four-leg or cross intersections); the majority of the sites examined were two-lane roads with traffic volumes ranging from 5,000 veh/day to 15,000 veh/day. The results from the meta-analysis are summarized in Exhibit 4-22 and Exhibit 4-23. This study was considered to be of medium-high quality due to the rigorous methodology applied by Elvik and Vaa, and the standard error values have been multiplied with a method correction factor of 1.8 to compensate for this. The study results were not combined due to the differences in crash severity and type of intersections (T-intersection versus cross intersection).

Exhibit 4-22: Safety effectiveness of adding right-turn lanes through physical channelization at T-intersections

Author, date	**Treatment / Element**	**Setting**	**Intersection type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa, 2004	Physical channelization of right-turn lane on major road	Mostly rural	T-intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, Injury	0.98	0.63

Exhibit 4-23: Safety Effectiveness of Adding Right-turn Lanes through physical channelization at Four-leg/Cross intersections

Author, date	**Treatment/ Element**	**Setting**	**Intersection type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa, 2004	Physical channelization of right-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, Injury	0.87	1.94
Elvik and Vaa, 2004	Physical channelization of right-turn lane on major road	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, PDO	0.81	0.84

Harwood et al. investigated the safety effectiveness of adding right-turn lanes with a before-after study using a combination of three approaches: the yoked comparison (YC) or matched-pair approach, the comparison group approach (CG), and the Empirical Bayes (EB) approach. In descending order of appropriateness, results from the EB approach were deemed to be the most credible followed by the results from the CG approach and then the YC approach (*22*). For cases where the EB result was not statistically significant but the CG or YC result was statistically significant, the result from CG or YC approach was adopted as the final result. The intersections studied were located in both urban and rural areas, and were either traffic signal controlled or two-way stop-controlled. For the sites examined, traffic volumes had a range of

1,600 to 55,100 veh/day for major road ADT, 25 to 26,000 veh/day for minor road ADT, and 1,100 to 62,300 veh/day for total entering ADT, respectively.

The results from the study quantifying the safety effect of adding a right-turn lane on a single major road approach at either T-intersections or four-leg/cross intersections are shown in Exhibit 4-24. The safety impact of adding a right-turn lane on both major road approaches at four-leg/cross intersections are summarized in Exhibit 4-25. These results were assigned a high rating; a MCF of 1.2 was applied to the s ideal calculated using reported standard error values.

Exhibit 4-24: Safety Effectiveness of Adding Right-turn Lanes on One Major Road Approach at T- or Four-leg/Cross Intersections

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of right-turn lane on single major road approach	Mixed urban and rural	Stop-controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, all severities	0.86	0.06
Harwood et al., 2002	Installation of right-turn lane on single major road approach	Mixed urban and rural	Traffic signal controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, all severities	0.96	0.02
Harwood et al., 2002	Installation of right-turn lane on single major road approach	Mixed urban and rural	Stop-controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, Fatal and Injury	0.77	0.08
Harwood et al., 2002	Installation of right-turn lane on single major road approach	Mixed urban and rural	Traffic signal controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, Fatal and Injury	0.91	0.04

Exhibit 4-25: Safety Effectiveness of Adding Right-turn Lanes on Both Major Road Approaches at Cross Intersections

Author, date	Treatment/ Element	Setting	Intersection Type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Installation of right-turn lane on both major road approaches	Mixed urban and rural	Stop-controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, all severities	0.74	0.08
Harwood et al., 2002	Installation of right-turn lane on both major road approaches	Mixed urban and rural	Traffic signal controlled T- or Four-leg/cross intersections, major road 1,600 to 55,100 veh/day, minor road 25 to 26,000 veh/day	All types, all severities	0.92	0.03
Harwood et al., 2002	Installation of right-turn lane on both major road approaches	Mixed urban and rural	Stop-controlled T- or Four-leg/cross intersections	All types, fatal and injury	0.59	n/a
Harwood et al., 2002	Installation of right-turn lane on both major road approaches	Mixed urban and rural	Traffic signal controlled T- or Four-leg/cross intersections	All types, fatal and injury	0.83	n/a

Discussion: Provide positive offset for right-turn lanes

None of the studies examined provided any empirically-based evidence of accident reductions resulting from the implementation of positive offsets for right-turn lanes. However, it is likely that such a treatment helps to reduce the potential for accidents between vehicles turning left, turning right, or crossing from the minor road and through vehicles on the major road since vehicles in the right-turn lanes no longer obstruct the view of those drivers (*10*).

Discussion: Provide right-turn acceleration lanes at intersections

By removing the slower right-turning vehicles from through lanes, this treatment is expected to reduce rear-end and sideswipe accidents resulting from conflicts between vehicles turning right onto the highway and through vehicles on the highway (*10*). No quantitative estimates of the safety effectiveness of this treatment are available. Neuman et al. identified two potential areas of concern with regards to the use of right-turn acceleration lanes at intersections. First, the length of the lanes is critical since excessively long acceleration lanes may be mistaken as an additional through lane, resulting in additional conflicts due to last-minute lane changes; second, the installation of right-turn acceleration lanes increases the overall width of the intersection, and this in turn may cause potential problems for pedestrians crossing the intersection (*10*).

Treatment: Channelization on both major and minor roads at intersections

Elvik and Vaa meta-analyzed a number of studies that investigated the combined safety effects of adding left- and right-turn lanes at intersections using both physical (e.g. using traffic islands) and painted treatments (5). Elvik and Vaa report that the use of this particular type of treatment decreased injury accidents and PDO accidents at T-intersections and four-leg/cross intersections. However, the authors noted that there appeared to be an increase in injury accidents following the implementation of physical channelization of minor and major roads at T-intersections (p. 293) (5). The majority of the sites examined were two-lane roads with traffic volumes ranging from 5,000 to 15,000 veh/day. The results from the meta-analysis are summarized in Exhibit 4-26 and Exhibit 4-27. This study was considered to be of medium-high quality and the standard error values have been multiplied with a method correction factor of 1.8 to account for this.

Exhibit 4-26: Safety effectiveness of adding channelization on both major and minor roads at T-intersections

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Physical channelization of both major and minor roads	Mostly rural	T-intersections, mostly 2-lane roads, 5,000 to 15,000 veh/day	All types, Injury	1.16	0.16

Exhibit 4-27: Safety effectiveness of adding channelization on both major and minor roads at four-leg/cross intersections

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Physical channelization of both major and minor roads	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, Injury	0.73	0.10
Elvik and Vaa, 2004	Physical channelization of both major and minor roads	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	All types, PDO	0.87	0.40
Elvik and Vaa, 2004	Painted channelization of both major and minor roads	Mostly rural	Four-leg/cross intersections, mostly 2-lane roads , 5,000 to 15,000 veh/day	Injury Accidents	0.43	0.12

Treatment: Install by-pass lanes

Preston and Schoenecker conducted a naïve before-after study to investigate the safety effectiveness of by-pass lanes at stop-controlled three- and four-leg intersections on two-lane and multi-lane rural highways (*20*). Results from the study are summarized in Exhibit 4-28. Traffic volumes at the study sites were not provided in the reference. The study was assigned a low rating due to the methodology applied and lack of detail provided; the values for the indices of effectiveness were calculated using available crash data and a MCF of 2.2 was applied to the s ideal calculated based on the number of before crashes and the ratio of after/before duration. The study results were not combined due to the differences in crash severity.

Exhibit 4-28: Safety Effectiveness of Adding By-Pass Lanes at Intersections

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Preston and Schoenecker, 1999	Addition of left- or right-turn by-pass lanes	Rural	Stop-controlled T- or Four-leg/cross intersections, volumes not reported	All types, all severities	0.95	0.21
Preston and Schoenecker, 1999	Addition of left- or right-turn by-pass lanes	Rural	Stop-controlled T- or Four-leg/cross intersections	All types, Fatal and Injury	1.25	0.46
Preston and Schoenecker, 1999	Addition of left- or right-turn by-pass lanes	Rural	Stop-controlled T- or Four-leg/cross intersections	All types, PDO	0.81	0.23

Discussion: Introduce right-turn channelization

Much of the research conducted to assess the safety effectiveness of right-turn channelization is dated (i.e., 20 to 40 years old). Insufficient data were presented in the references reviewed to ascertain or calculate specific AMFs.

However, as noted by Fitzpatrick et al., "The effectiveness of various safety improvement projects was evaluated in the early 1970's by Dale. He found that channelization of intersections produced an average 32.4 percent reduction in all types of accidents. Accidents involving personal injuries decreased by more than 50 percent" (page 81,(*23*)). Further details of the projects were not reported by Fitzpatrick et al.

Similar results were noted by McCoy et al. (1995). The findings of this research are summarized by Harwood on pages 40 and 41 of the NCHRP Interim Report 17-26 - Methodology to Predict the Safety Performance of Urban and Suburban Arterials:

"In general, studies indicate that channelization improves safety in urban and suburban areas. David and Norman found that raised pavement markings tended to decrease accidents, especially at three-leg intersections. Exnicios determined that several safety measures, including channelization, resulted in a 31 percent reduction in total accidents (over two years), a 58 percent reduction in total accidents (over one year), and a 100 percent reduction in total

accidents (over 26 months) at several suburban intersections located in or near several metropolitan areas. Rowan and Williams found accident rates, personal injuries and rear-end type accidents were reduced due to the introduction of channelization at intersections in northwest Houston."

Harwood also presents findings for channelization at rural intersections. On page 40 of the same document, he notes:

"In developing guidelines for channelized right-turn lanes at unsignalized intersections on rural two-lane highways, McCoy et. al. (1995) evaluated the safety effects of channelized right-turn lanes. An analysis of the accident history at 89 rural intersections with and without channelized right-turn lanes over a five-year period found no effect of channelized right-turn lanes on the frequency, severity, or types of accidents that occur on approaches to unsignalized intersections. Thus, based upon the accident analysis it was concluded that channelized right-turns do not provide the road user with any safety benefits or disbenefits."

However, the methodologies applied to yield these results are somewhat dated and may not account for confounding factors, regression-to-mean, etc. Current research being conducted for Part III of the HSM may produce quantification of the safety effect of channelization.

4.1.2.2. Shoulders

AASHTO defines the shoulder of a roadway as "the portion of the roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use, and lateral support of subbase, base, and surface courses" (*2*). In some cases, the shoulder can also accommodate bicyclists. Hauer adds that while the original intent of shoulders was to provide for vehicles that have to stop for involuntary or emergency stops, the full shoulder also induces some amount of voluntary stopping. Vehicles stopped on shoulders may have a negative effect on safety (*24*).

There is also the possibility that wider shoulders may lead to higher travel speeds. Even small increments in the mean speed have noticeable impact on accident severity (*24*). Additional discussion of shoulders is provided in Section 3.1.

Sidewalks or walkways are "pedestrian lanes" that provide people with space to travel within the public right-of-way that is separated from roadway vehicles (*25*). Sidewalks are considered to be an integral part of city streets but are rarely provided in rural areas despite there being a higher potential for accidents with pedestrians due to higher speeds and the general absence of lighting. In urban areas, when pedestrians encounter an intersection, there is a major interruption in pedestrian flow and as such, the sidewalk should provide sufficient storage area for those waiting to cross as well as an area for pedestrian cross traffic to pass (*2*).

There are several resources available for sidewalk and shoulder design elements, such as: NCHRP 254 "Shoulder Geometrics and Use Guidelines" contains further detailed information about the design elements of roadway shoulders; AASHTO's "Guide for the Development of Bicycle Facilities" provides more information on the use of shoulders to accommodate bicyclists; and AASHTO's "Guide for the Planning, Design, and Operation of Pedestrian Facilities" (*26*) contains further guidance on sidewalk design elements.

Section 3.1 contains further information on the safety impacts of shoulders on roadway segments, and Section 3.2 discusses the safety impacts of on-street parking. Section 4.3 contains more information on pedestrian and bicyclist safety at intersections.

This section examines the safety effects of the various geometric design elements related to shoulders and sidewalks at intersections. The discussion in this section excludes any consideration for these facilities at mid-block or along roadway segments since these issues are addressed Chapter 3.

Exhibit 4-29: Resources examined to investigate the safety effect of shoulders and sidewalks at intersections

DOCUMENT	**DESCRIPTION**	**COMMENT**
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities	Not added to synthesis. No quantitative or qualitative information on safety impacts found.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing the effects of various road safety measures and treatments using a meta-analytical approach.	Not added to synthesis. Information found more relevant to sections of road segments.
(*18*) NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	Interim report for study designed to develop a methodology to predict the safety performance of various elements such as Lane width, Shoulder width and curbs, etc. on urban and suburban arterials.	Added to synthesis. Only non empirical-based and anecdotal information found based on literature review. No quantitative evidence of safety impacts found because reference is only a draft interim report—the models have not been developed at this time
(Zegeer, C. V., Seiderman, C., Lagerwey, P., Cynecki, M. J., Ronkin, M., and Schneider, R., "Pedestrian Facilities Users Guide - Providing Safety and Mobility." FHWA-RD-01-102, McLean, Va., Federal Highway Administration, (2002))	Report describes pedestrian crash trends and potential safety treatments. The report does not include accident modification factors	Added to Section 4.3
(*24*) (Hauer, E., "Shoulder Width, Shoulder Paving and Safety." (2000))	Report is an extensive review of the empirical evidence on the safety effects of shoulder width. It includes comments on paved/unpaved shoulders	Added to synthesis. Some discussion on the geometric design elements of shoulders is presented. Regression equation cited from study by Washington et al. relating shoulder width to accident rates included. S value calculated using available information from original study.
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Report is a detailed study of the operational and safety considerations of median widths at 40 rural and suburban divided highway intersections	Not added to synthesis. Reference is more relevant to Medians

Based on available literature on the topic, it appears that the majority of safety studies that deal with shoulders focus on the safety impacts of shoulders on road segments rather than at intersections. A critical review of the references identified previously, along with a preliminary review of references available through TRIS, yielded limited accident modification factors for the geometric design issues related to either shoulders or sidewalks at intersections. The critical review shows that there is an abundance of empirical-based evidence of safety impacts for shoulders on road segments, particularly as they relate to shoulder widths. With regards to the transferability of findings from studies examining shoulders for road segments, it is prudent to withhold from drawing any conclusions based on studies that examined road segments rather than intersections because of the complex nature of the mechanism through which safety is affected. As Hauer points out, the study of the safety impacts of shoulders is “both complex and perhaps variable in time and place”.

Hauer further adds that “one may conduct a study on straight and level road sections only to find later that the results are different on curvy roads or roads with a large grade”. With results being so ambiguous and occasionally even contradictory for road segments alone, it is clearly prudent to refrain from drawing similar conclusions about shoulders at intersections, particularly given that driver behavior and expectations are very different at intersections compared to road segments.

Discussion: Widen shoulder at intersections

As it stands, few empirically-based studies focus on the safety effects of the various design elements associated with shoulders at intersections. Harwood et al. reviewed a number of previous research studies and found inconclusive evidence on the safety impacts of wide shoulders at intersections. For instance, Bauer and Harwood reported that increasing the shoulder width at rural intersections tends to decrease accidents while David and Norman did not find any evidence that incremental changes in shoulder width near intersections affected accident rates (*18*). No AMFs could be derived from these studies for rural intersections.

Hauer carried out a comprehensive review of studies examining the safety effects of shoulder widths, including a study by Washington et al. (1991) that examined the safety effects of various geometric design elements on high-speed, isolated, signalized intersections in urban or suburban environments (*24*). The traffic volumes for the sites used in the study were not reported. Hauer found that wide paved shoulders were statistically significantly associated with lower accident rates.

Based on review of a study by Washington et al., Hauer reported that the number of accidents for high-speed, isolated intersections prediction could be calculated using Equation 1 and Equation 2 (*24*). An approach was considered to be high-speed if any of the following criteria were met: (a) it had an observed mean speed of 45 mph or greater; (b) it had an observed 85^{th} percentile speed of 50 mph or greater; (c) it was a state highway approach with no posted speed limit; (d) it had a posted speed limit of 50 mph or greater; (e) site visit by researchers showed intersection to have no traffic control within 5 miles of intersection and had high-speed traffic. Given the form of the equations, AMFs and corresponding standard error values could not be derived.

Equation 1: Regression Equation Relating Total Accidents with Shoulder Width at Isolated, High-Speed Intersections, for all approaches (24)

$$\text{Total Accidents per million entering vehicles} = 2.81 - 0.19 \times \text{paved shoulder width [ft]}$$

$$S = 0.05$$

Equation 2: Regression Equation Relating Total Accidents on High-Speed Approaches with Shoulder Width at Isolated, High-Speed Intersections, for high speed approaches (24)

Total Accidents for the high-speed approach per million entering vehicles for that approach = 3.24 - 0.27×paved shoulder width [ft]

S = 0.06

4.1.2.3. Medians

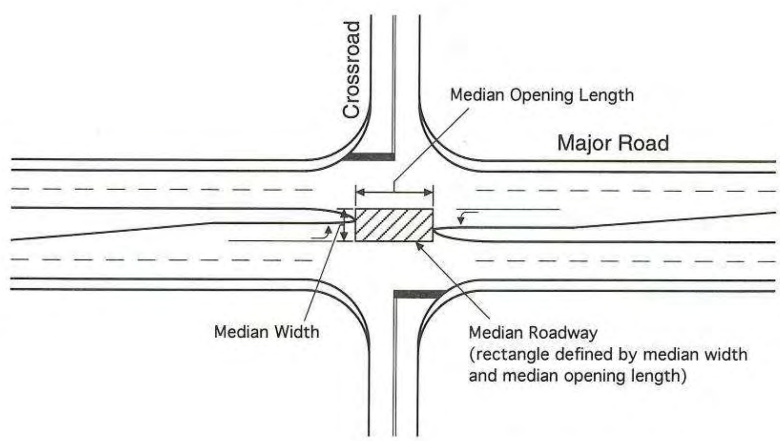
The AASHTO Green Book defines a median as "the portion of a highway separating opposing directions of the traveled way" (*2*). Further, the principle functions of a median are to separate opposing traffic, provide a recovery area for out-of-control vehicles, provide a stopping area in case of emergencies, allow space for speed changes and storage of left-turning and U-turning vehicles, minimize headlight glare, and provide width for future lanes (*2*). Additional benefits of a median include the possibility of an open green space, and providing a refuge area for pedestrians crossing the street.

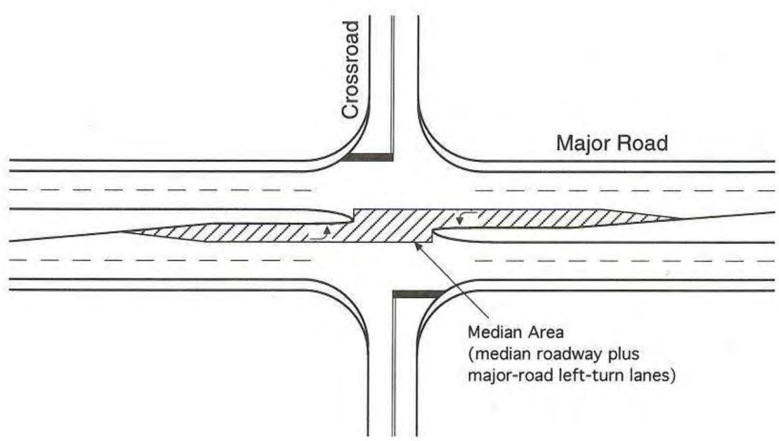
Three other commonly used terms are defined in the "Median Intersection Guide" (*21*):

- Median roadway: paved area in the center of the divided highway at an intersection defined by the median width and the median opening length
- Median area: median roadway plus the major-road left-turn lanes (if any)
- Median width: total width between the edges of opposing through lanes, including the left shoulder and the left-turn lanes (if any)

The median roadway, median area and width are illustrated in Exhibit 4-30. The design of a median opening and median ends should be based on traffic volumes, urban/rural area characteristics, and type of turning vehicles (*2*).

Exhibit 4-30: Definition of Median Roadway and Median Area (21)





At intersections, special concern should be given to the median width because, as indicated in NCHRP Report 375, most types of undesirable driving behavior in the median areas of divided highway intersections are associated with competition for space by vehicles traveling through the median in the same direction. The potential for such problems is limited where crossroad and U-turn volumes are low, but may increase at higher volumes (*21*).

Medians have to be wide enough to accommodate and protect left-turning or U-turning vehicles but not so wide that drivers become confused about the correct path to follow while on the median roadway. Median widths generally range from 4 ft to 80 ft (1.2 m to 24 m) or more. On divided highways without at-grade intersections, the median may be as narrow as 4 ft to 6 ft (1.2 m to 1.8 m) under very restricted conditions but that a median width of 60 ft (20 m) or more should be provided wherever possible. Medians 12 ft to 30 ft (3.6 m to 9 m) are preferred because they provide the necessary protection for left-turning vehicles at intersections. Median widths in the 30 ft to 50 ft (9 m to 15 m) range also provide protection for left-turning vehicles but do not allocate enough storage space for larger vehicles such as buses and trucks. Median widths of 80 ft (25 m) or more may be needed to accommodate large tractor-trailer trucks without encroaching on the through lanes of a major road. Despite this challenge, intersections on divided highways with median widths in the 30 ft to 50 ft (9 m to 15 m) range are deemed to operate well (*2*).

The AASHTO Green Book (*2*) and NCHRP Report 375 (*21*) provide information on the design criteria for medians at intersections.

This section discusses the safety effects of providing medians at intersections on rural multilane highways, different median widths at intersections on rural multi-lane highways, including freeways, and urban and suburban arterials. Section 3.1 provides additional information on the safety effects of medians on roadway segments. Section 4.3 discusses the impacts of intersection design on pedestrians and bicyclists.

Exhibit 4-31: Resources examined to investigate the safety effect of medians at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*126*) (Jonsson, T., Ivan, J.N., and Zhang, C., Crash Prediction Models for Intersections on Rural Multilane Highways: Differences by Collision Type, Transportation Research Record 2019, (2007), pp. 91-98)	Negative binomial regression models were estimated relating the frequency of different types of crashes on stop controlled intersections on rural multilane roads with many intersection and approach characteristics. Independent variables include many site characteristics including whether there was a median	Added to synthesis.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results may be added if relevant when available.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing the effects of various road safety measures and treatments using a meta-analytical approach.	Not added to synthesis. Material in reference is related to medians on roadway segments rather than intersections.
(Xu, L., "Right Turns Followed by U-Turns Versus Direct Left Turns: A Comparison of Safety Issues." ITE Journal, Vol. 71, No. 11, Washington, D.C., Institute of Transportation Engineers, (2001) pp. 36-43.)	Cross-sectional study comparing accident rates and accident frequencies between direct left turns and an alternative left-turn design (i.e. right-turn, followed by U-turn)	Not added to synthesis. Treatment being examined is the type of left-turn configuration and not directly related to the design of the median itself. Reference is more relevant to intersection types and alternative left-turn treatments.
(Dixon, K. K., Hibbard, J. L., and Nyman, H., "Right-Turn Treatment for Signalized Intersections." Dallas, Tex., Urban Street Symposium Conference Proceedings, (1999))	Paper briefly discusses various intersection treatments, but does not provide accident data. It also discusses the potential safety impacts of five common right-turn treatments.	Not added to synthesis. Reference more relevant to Lanes.

DOCUMENT	DESCRIPTION	COMMENT
(*21*) (Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Report is a detailed study of the operational and safety considerations of median widths at 40 rural and suburban divided highway intersections.	Added to synthesis. AMFs were calculated using reported percentage reductions in accidents resulting from regression equations. s values were computed using reported standard error values.
(Bowman, B. L. and Vecellio, R. L., "Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety." Transportation Research Record 1445, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 169-179.)	Study compared accident rates for arterials to determine the effects of median treatments on vehicular and pedestrian accidents	Not added to synthesis. Focus of study is on safety effect of medians at midblock. While some information is presented on intersections, there is insufficient data to calculate t and s values.
(Maze, T. H., Henderson, J. L., and Sankar, R., "Impacts on Safety of Left-Turn Treatment at High Speed Signalized Intersections." HR-347, Ames, Iowa Highway Research Board, (1994))	Study investigated the safety effects of left-turn treatment at high speed signalized intersections at 63 intersections in Iowa.	Not added to synthesis. Regression models developed in study are additive in form and cannot be used to calculate AMF values, as verified by Hauer.
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)	Study developed linear regression equations to compare different intersection treatments, including median type and width.	Not added to synthesis. Comments by reviewers were highly critical of findings, particularly with regards to the recommendation by authors of raised medians over flat medians.
(Harwood, D. W., "NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways." Washington, D.C., Transportation Research Board, National Research Council, (1986))	Cross-sectional study that examined the safety effects of a number of design parameters on unsignalized intersection crashes	Not added to synthesis. More recent study by same author supersedes results from this reference.

The safety effectiveness of wider medians has been quantified for rural multi-lane highways and urban and suburban arterials. No studies for rural two-lane highways were found. It appears that few studies that examine the safety effects of medians focus on intersections; the large majority deals with median widths (and other median design parameters) on roadway segments. The only study from which AMFs and corresponding standard error values were derived did not report any traffic volumes but did provide information on the range of validity for median widths.

Treatment: Introduce medians at intersections

Jonsson et al. estimated regression models to relate single vehicle, angle, opposite direction, same direction, and total crashes with intersection characteristics at stop-controlled intersections on rural multilane roads in California (*126*). The sample included 378 T intersections and 264 cross intersections. Presence or absence of a median was included as an indicator variable in these models. However, since introducing a median can be correlated with the presence or absence of left-turn lanes, the results from this study were not used to develop AMFs for introducing medians at intersections.

Treatment: Widen median widths at intersections

Harwood et al. developed regression equations to represent expected changes to multiple-vehicle accidents resulting from changes to median widths at rural four-leg unsignalized intersections, urban/suburban four-leg unsignalized intersections, urban/suburban three-leg unsignalized intersections, and urban/suburban four-leg signalized intersections (*21*). While the equations themselves were not reported in the study, results were tabulated in terms of percentage changes to total multiple-vehicle accidents and fatal/injury multiple-vehicle accidents resulting from unit increases to median widths at these types of intersections. This tabulation of results is shown in Exhibit 4-32.

In summary, Harwood et al. found that as median widths increase, accidents decrease for rural, four-leg intersections. In contrast, accident frequencies increased for urban/suburban three- and four-leg unsignalized intersections and four-leg signalized intersections. AMFs and corresponding standard error values were estimated using the results from the study and are summarized in Exhibit 4-33. These values are valid over the range of median widths from 14 to 80 ft (4 to 24 m). A method correction factor of 1.5 was applied to the s ideal calculated using reported 95% confidence interval values.

Exhibit 4-32: Summary of Safety Effects Resulting from Changes to Median Width (21)

	Median width effect expressed as a percentage change in accident frequency					
	Per unit change of 1 m in median width			Per unit change of 1 ft in median width		
Intersection type	Estimate (%)	Lower 95% confidence limit	Upper 95% confidence limit	Estimate (%)	Lower 95% confidence limit	Upper 95% confidence limit
TOTAL MULTIPLE-VEHICLE ACCIDENTS						
Rural 4-leg unsignalized	-4.16	-6.30	-2.00	-1.22	-1.92	-9.61
Rural 3-leg unsignalized	-	-	-	-	-	-
Urban/suburban 4-leg unsignalized	5.67	4.23	7.08	1.73	1.29	2.16
Urban/suburban 3-leg unsignalized	2.69	1.11	4.26	0.82	0.34	1.30
Urban/suburban 4-leg signalized	3.02	1.11	4.97	0.92	0.34	1.50
FATAL AND INJURY MULTIPLE-VEHICLE ACCIDENTS						
Rural 4-leg unsignalized	-4.43	-7.15	-1.67	-1.35	-2.18	-0.51
Rural 3-leg unsignalized	-	-	-	-	-	-
Urban/suburban 4-leg unsignalized	5.25	3.21	7.31	1.60	0.98	2.23
Urban/suburban 3-leg unsignalized	-	-	-	-	-	-
Urban/suburban 4-leg signalized	2.92	1.11	4.72	0.89	0.34	1.44

Exhibit 4-33: Safety Effectiveness of Widening Medians at Intersections

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Rural	Four-leg unsignalized intersections, volume not reported	Multiple-vehicle accidents, all severities	0.958	0.016
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Urban/ suburban	Four-leg unsignalized intersections, volume not reported	Multiple-vehicle accidents, all severities	1.057	0.011

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Urban/ suburban	Three-leg unsignalized intersections, volume not reported	Multiple-vehicle accidents, all severities	1.027	0.012
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Urban/ suburban	Four-leg signalized intersections, volume not reported	Multiple-vehicle accidents, all severities	1.030	0.014
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Rural	Four-leg unsignalized intersections, volume not reported	Multiple-Vehicle Accidents, Fatal and Injury	0.9557	0.021
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Urban/ suburban	Four-leg unsignalized intersections	Multiple-Vehicle Accidents, Fatal and Injury	1.0525	0.015
Harwood et. al, 1995	Widening median by 3 ft (1 m)	Urban/ suburban	Four-leg signalized intersections	Multiple-Vehicle Accidents, Fatal and Injury	1.0292	0.014

4.1.3. Roadside Elements

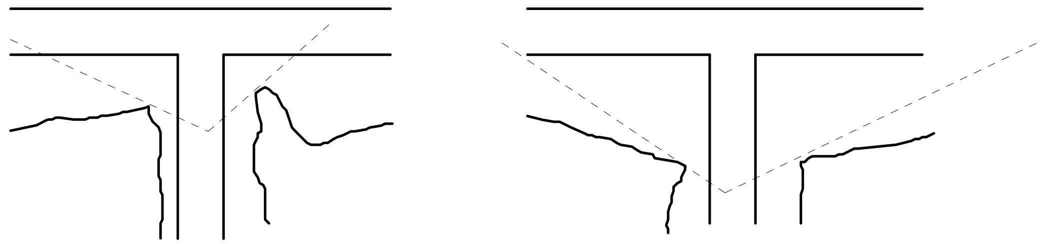
This section will provide information on the safety effect of roadside elements (e.g., geometry, features and barriers) on the approach to an intersection. This section will add to the knowledge presented for roadway segment roadside elements in Section 3.1.

4.1.3.1. Roadside Geometry

Roadside geometry is discussed in Section 3.1 for roadway segments. This section will add to that discussion with roadside geometry design specific to intersections. A key consideration at intersections is the triangle sight distance. Limited sight distance can make it difficult to detect the intersection itself or entering vehicles in time to stop safely. This section discusses approach sight triangles and departure sight triangles (as defined in AASHTO's Green Book (*2*)) at intersections.

Intersection triangle sight distance is illustrated in Exhibit 4-34. In a three-leg junction, there are two triangles. In a four-leg intersection, there are four triangles.

Exhibit 4-34: Intersection triangle sight distance



According to the AASHTO Green Book, curbs serve any or all of the following purposes: drainage control, roadway edge delineation, right-of-way reduction, aesthetics, delineation of pedestrian walkways, reduction of maintenance operations, and assistance in orderly roadside development. It adds that a curb, by definition, incorporates some raised or vertical element. A curb may be designed as a separate unit or in combination with the pavement. Vertical and sloping curb designs may include a gutter, forming a combination curb and gutter section as is typically used in urban settings (*2*). The AASHTO Green Book (*2*) provides information on the design of curbs.

This section of the HSM is intended to discuss the safety effects of different elements on the roadside of roadway segments at intersections. Chapter 3 of the HSM contains further information on roadside geometry on roadway segments.

Exhibit 4-35: Resources examined to investigate the safety effect of roadside geometry at intersections

DOCUMENT	DESCRIPTION	COMMENT
(5) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing the effects of various road safety measures and treatments using a meta-analytical approach.	Added to synthesis.
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	No AMFs. Not added to synthesis.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results not available.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	Cites Harwood et al (2000). Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Compilation of data including safety, geometric, and traffic with a broad range of suggested countermeasures	Too few details to be included in meta-analysis.

DOCUMENT	DESCRIPTION	COMMENT
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Sight distance due to roadway aliment or terrain was considered for the crash prediction algorithm.	Does not contain original studies relevant for this section. Not added to synthesis.
(Harwood, D. W., Mason, J. M., Brydia, R. E., Pietrucha, M. T., and Gittings, G. L., "NCHRP Report 383: Intersection Sight Distance." Washington, D.C., Transportation Research Board, National Research Council, (1996))	Research on the current procedure employed by AASHTO ISD methodology. Conclusions and recommendations on the ISD design procedures	No AMFs. Not added to synthesis.
(Carnahan, C. R., Fox, W. C., French, K. A., Hange, W. A., Henderson, J. L., Hook, D. J. P., Imansepahi, A., Khattak, S. S., Paulson, J. D., Resseguie, J. K., Richey, J. M., and Searls, T. D., "Permissive Double Left Turns: Are They Safe?" Washington, D.C., ITE 1995 Compendium of Technical Papers, (1995) pp. 214-218.)	This study incorporated a literature review, a survey of state DOT's and some local agencies, a review of data collected at traffic signals in the Denver and Colorado Springs areas, and a delay study of a corridor in Denver	No AMFs. Not added to synthesis.
(Kulmala, R., "Safety at Rural Three- and Four-Arm Junctions: Development and Application of Accident Prediction Models." 233, Espoo, Finland, VTT Technical Research Centre of Finland, (1995))	Research based on an inventory of 2,700 junctions where a model of 915 three-arm and 847 four-arm junctions were modeled	Added to synthesis (from a 1992 report by the same author).
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))	Report is a detailed study of the operational and safety considerations of median widths at 40 rural and suburban divided highway intersections.	Not added to synthesis.
(Kuciemba, S. R. and Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume V - Intersections." FHWA-RD-91-048, Washington, D.C., Federal Highway Administration, (1992))	A review incorporating a variety of studies including accident data, facility design guidelines, route designation criteria, and evaluations of facilities based on observational analysis accident data	No AMFs. Not added to synthesis.

Treatment: Increase sight triangle

Only a few studies evaluating the safety effects of increasing sight triangles in intersections have been found. These studies have been previously studied by Elvik and Vaa (2004) (*5*), and are listed in Exhibit 4-36.

Exhibit 4-36: Studies evaluating the safety effects of increasing triangle sight distance in intersections (5)

Study	Country	Design	Number of estimates
Johannessen and Heir 1974	Norway	Cross-sectional study	16
Hanna, Flynn and Tyler 1976	United States	Cross-sectional study	1
Vaa and Johannessen 1978	Norway	Cross-sectional study	6
Brüde and Larsson 1985	Sweden	Empirical Bayes before-after	1

Study	Country	Design	Number of estimates
Vodahl and Giæver 1986	Norway	Cross-sectional study	1
Kulmala 1992	Finland	Empirical Bayes before-after	4

All of these studies are fairly old and none of them employ current state-of-the art design or techniques for analysis. Most of the studies are cross-section studies that compare accident rates in intersections that differ with respect to the shortest sight distance found in any of the triangles. These studies do not control for any confounding factors. The standard error of the estimate of effect in these studies has been increased by a factor of 5. The studies cover minimum sight distances ranging from 65 ft (20 m) to 490 ft (150 m). Only two studies are before-and-after studies; both of them employed an Empirical Bayes design that controls for regression-to-the-mean. In both studies, however, this design was somewhat simpler than the current state-of-the-art Empirical Bayes design. The standard error of the estimates of effect in these studies has been increased by a factor of 1.8.

Not all studies state the increase in sight distance evaluated. In studies stating the size of the difference in sight distance being compared, the difference ranges from about 65 ft (20 m) to about 195 ft (60 metres). The estimates given in Exhibit 4-37 refer to all increases in sight distance, and not just those within a particular range. The studies do not make it clear if this is approach sight distance or departure sight distance.

Exhibit 4-37: Summary estimates of the effect of increasing triangle sight distance in intersections

Author, date	Treatment/ Element	Setting	Intersection Type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Increasing triangle sight distance	Not reported	Three leg, volume not reported	All types, Injury (7)	1.296	0.570
Elvik and Vaa, 2004	Increasing triangle sight distance	Not reported	Three leg, volume not reported	All types, PDO (1)	1.290	0.771
Elvik and Vaa, 2004	Increasing triangle sight distance	Not reported	Four-leg, volume not reported	All types, Injury (11)	0.525	0.288
Elvik and Vaa, 2004	Increasing triangle sight distance	Not reported	Four-leg, volume not reported	All types, PDO (10)	0.892	0.154

NOTE: The number in brackets beside the index of effectiveness indicates the number of estimates used to generate the result.

At three-leg intersections, there is a tendency for the number of accidents to increase, as shown in Exhibit 4-37. The standard errors are very wide, showing that the evidence of effect in three-leg intersections is highly limited. In four-leg intersections, the number of accidents is reduced. This applies both to injury accidents and to property-damage-only accidents, but the largest accident reduction is found for injury accidents. Most of the intersections studies were rural and controlled by yield signs. The estimates are highly uncertain. There is clearly a need for more research.

4.1.3.2. Roadside Features

Roadside features may include signs, signals, luminaire supports, utility poles, trees, motorist-aid call boxes, railroad crossing warning devices, fire hydrants, mailboxes, bus shelters, and other similar roadside features. Roadside features are sometimes referred to as street furniture.

The AASHTO Roadside Design Guide contains information about the placement of these features, criteria for breakaway supports, base designs, among others (*27*).

This section provides discussion on relocating signal hardware out of the intersection clear zone, and minimizing or relocating roadside features at roundabouts. No AMFs could be developed based on available literature.

In future editions of the HSM, this section may provide quantified information on the safety effect of various roadside features on the approach to an intersection in the context of both rural and urban environments; for two-lane roads, multi-lane highways and urban and suburban arterials.

Roadside features on roadway segments are discussed in Section 3.1.

Exhibit 4-38: Resources examined to investigate the safety effect of roadside features at intersections.

DOCUMENT	DESCRIPTION	COMMENT
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Various strategies to mitigate crashes at signalized intersections.	Qualitative information only. Added to synthesis.
(Lacy, K., Srinivasan, R., Zegeer, C. V., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 8: A Guide for Addressing Accidents Involving Utility Poles." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies to mitigate accidents with utility poles.	Qualitative discussion of strategies. No AMFs. Reader referred to original document for more information. Not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Various strategies to mitigate crashes at unsignalized intersections.	No relevant strategies. Not added to synthesis.
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Prediction models developed for two-lane rural roads.	No relevant information. Not added to synthesis.
(Vogt, A., "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized." FHWA-RD-99-128, McLean, Va., Federal Highway Administration, (1999))	Models developed for stop-controlled and signalized intersections.	Presence of roadside features not included in models. Not added to synthesis.

(*58*,*28*) (Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995), Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))	Summary of roundabout designs and accommodation of various road users.	Qualitative discussion of roadside features. Added to synthesis.

Discussion: Relocate signal hardware out of clear zone

Antonucci et al. describe various strategies to mitigate crashes at signalized intersections, including relocate signal hardware out of clear zone (*4*). Antonucci et al. provide the following guidance for traffic signal hardware (pg V-78):

- "traffic signal supports and controller cabinets should be located as far from the edge of pavement as is possible, especially on high-speed facilities, as long as this does not adversely affect visibility of the signal indications"
- "where there is an existing roadside barrier, the cabinet should be located behind the barrier when feasible"
- "if practical, signal supports in medians should be located to provide more than the minimum clearance required by the agency"

Crash data or other quantitative measures of effectiveness are not provided by Antonucci et al., however the authors state that relocating signal hardware out of the clear zone "should reduce the likelihood of vehicles" colliding with the hardware (*4*). More information about the attributes of this strategy and others can be found in NCHRP Report 500 Volume 12.

Discussion: Minimize or relocate roadside features at roundabouts

Brown provides a brief discussion on the presence of roadside features (or furniture) at roundabouts based on international experience (*58*,*28*). Brown states "essential 'furniture' should be minimized on the central island (and deflection islands), and together with the lighting columns, should be located clear of over-run paths and visibility envelopes" (pg 156) (*28*). The safety effect of minimizing or relocating roadside features is not quantified.

4.1.3.3. Roadside Barriers [Future Edition]

As defined by AASHTO's Roadside Design Guide, a roadside barrier (guardrail, guiderail) is "a longitudinal barrier used to shield motorists from natural or man-made obstacles located along either side of a traveled way. It may also be used to protect bystanders, pedestrians, and cyclists from vehicular traffic under special conditions" (*27*). In future editions, this section of the HSM may discuss the safety effect of implementing roadside barriers on intersection approaches, including roundabouts. No potential resources have been identified for this section.

4.1.4. Alignment Elements [Future Edition]

The following sections will discuss the safety impact of horizontal and vertical curves on the approach to intersections and roundabouts.

4.1.4.1. Horizontal Alignment [Future Edition]

In future editions of the HSM, this section may provide information on the safety effect of the horizontal alignment of an approach to an intersection, and the safety effect of the position of an intersection within a curve. The effect that alignment has on sight distance and safety may be addressed. This section could compare crashes on intersection approaches that have horizontal curves to crashes on similar approaches that have straight alignments. The safety effect of realigning intersections or flattening approaches may be identified. This section will add to material presented in Section 3.1 for roadway segments. Potential resources are listed in Exhibit 4-39.

Exhibit 4-39: Potential resources on the safety relationship of horizontal alignment at intersections

DOCUMENT
(*132*) (Savolainen, P.T. and Tarko, A. "Safety Impacts at Intersections on Curved Segments", Transportation Research Record 1908, (2005), pp. 130-140.
(Yuan, F; Ivan, JN; Qin, X; Garrick, NW; Davis, CF,"Safety Benefits of Intersection Approach Realignment on Rural Two-Lane Highways", Transportation Research Record 1785, (2001))
(Harwood, D. W., Mason, J. M., Brydia, R. E., Pietrucha, M. T., and Gittings, G. L., "NCHRP Report 383: Intersection Sight Distance." Washington, D.C., Transportation Research Board, National Research Council, (1996))
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))

4.1.4.2. Vertical Alignment [Future Edition]

In future editions of the HSM, this section may provide information on the safety effect of the vertical alignment of an approach to an intersection. The effect that vertical alignment has on sight distance and safety may be addressed, and linked to the intersection roadside geometry and roadside barriers. This section could compare crashes on intersection approaches that have vertical curves to crashes on similar approaches that have flat alignments. The safety effect of realigning intersections or flatting approaches may be identified. This section will add to material presented in Section 3.1 for roadway segments. Potential resources are listed in Exhibit 4-40.

Exhibit 4-40: Potential resources on the safety relationship of vertical alignment at intersections

DOCUMENT
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))
(Yuan, F; Ivan, JN; Qin, X; Garrick, NW; Davis, CF,"Safety Benefits of Intersection Approach Realignment on Rural Two-Lane Highways", Transportation Research Record 1785, (2001))
(Harwood, D. W., Mason, J. M., Brydia, R. E., Pietrucha, M. T., and Gittings, G. L., "NCHRP Report 383: Intersection Sight Distance." Washington, D.C., Transportation Research Board, National Research Council, (1996))
(Harwood, D. W., Pietrucha, M. T., Wooldridge, M. D., Brydia, R. E., and Fitzpatrick, K., "NCHRP Report 375: Median Intersection Design." Washington, D.C., Transportation Research Board, National Research Council, (1995))
(Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995)) and (Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))

(Kuciemba, S. R. and Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume V - Intersections." FHWA-RD-91-048, Washington, D.C., Federal Highway Administration, (1992))

4.1.4.3. Combination Horizontal and Vertical Alignment [Future Edition]

In future editions of the HSM, this section may discuss the safety effects of combined horizontal and vertical alignment, possibly including design consistency and speed profiles. Consideration may be given to include discussion of driver preview of the road surface of the intersection, including pavement markings and other signs or signals. This section will add to material presented in Section 3.1 for roadway segments. Potential resources are listed in Exhibit 4-41.

Exhibit 4-41: Potential resources on the safety relationship of combined horizontal and vertical alignment at intersections

DOCUMENT
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))

4.2. Safety Effects of Intersection Traffic Control and Operational Elements

The following sections provide discussion of the safety effect of various traffic control and operational elements of intersections. Topics of discussion include the type of traffic control employed, traffic signal operations, warning beacons, signs, pavement markings, delineation, traffic calming, and ITS applications.

Topics for future editions of the HSM include speed limits and on-street parking near intersections.

Some important resources regarding intersection traffic control and safety are:

- “Manual on Uniform Traffic Control Devices”, FHWA 2003 (*17*)
- “Traffic Control Devices Handbook”, ITE 2001 (*29*)
- “Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians Volume: I: Final Report”, Staplin et al., 1997 (*30*)
- “Safety Effectiveness of Highway Design Features: Volume V – Intersections”, Kuciemba et al., 1992 (*31*)

4.2.1. Type of Traffic Control

A variety of traffic control devices may be used at the at-grade intersection of two streets or highways, including signalization, stop-control, and yield-control. Roundabouts are also being applied at intersections to increase capacity and safety. Converting the traffic control at an intersection may be prompted by safety or operational concerns.

The discussion in this section covers the relative safety effect of conversions of various intersection control types including:

- Stop-control to yield-control conversions;

- Two-way stop-controlled (TWSC) to all-way stop-controlled (AWSC);
- TWSC or AWSC to signalized;
- Signalized to stop-control.

Conversion of intersections to roundabouts and other intersection design changes are discussed in Section 4.1.1.

The impact of installation of signals by expanding the commonly known traffic signal warrant to include a safety warrant as documented in the MUTCD (*17*) will be included in this section. The suggested process was recently documented in the study “Crash Experience Warrant for Traffic Signals” by McGee et al. (*32*).

Where available, information is provided for 3-leg and 4-leg intersections and for various crash types and severities. Of particular importance are the relationships between the various methods of intersection control and their influences on rear-end and right-angle crash types.

Exhibit 4-42: Resources examined to investigate the safety effect of traffic control types at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*133*) (Harkey, D., et al., Accident Modification Factors for Traffic Engineering and ITS Improvements, *NCHRP Report* 617, TRB, 2008)	Estimated the safety impacts of replacing stop control with traffic signals at rural intersections. Before-after EB method was used.	Added to synthesis. t and s values provided in an exhibit.
(*134*) (Davis, G.A. and Aul, N., “Safety Effects of Left-Turn Phasing Schemes at High-Speed Intersections”, Minnesota Department of Transportation, Report No. MN/RC-2007-03, (2007))	Estimated the safety impacts of replaing signal control with traffic signals in intersections in urban areas with major road speed limit at least 40 mph. Before-after full Bayes method was used.	Added to synthesis. t and s values provided in an exhibit.
(*135*) (Hadayeghi, A., Malone, B., and De Gannes, R., Development of New Crash Experience Warrants for Traffic Signals in Ontario, *Transportation Research Record 1953*, (2006), pp. 120-127)	This paper recommends a safety analysis and evaluation tool for estimating the expected safety of the installation of traffic signals.	Not added to synthesis. The paper dees not provide AMFs.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook that summarizes the effects of a wide range of safety measures.	Not added to synthesis
(Hauer, E., "Left Turn Protection, Safety, Delay and Guidelines: A Literature Review." (2004))	A compilation of various research that analyzes safety of various left turn phasing operations	Not added to this synthesis.
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Provides a plan for an integrated, multi-disciplinary approach to addressing crashes and safety. Material not relevant for this subsection.	Not added to synthesis
(*32*) (McGee, H., Taori, S., and Persaud, B. N., "NCHRP Report 491: Crash Experience Warrant for Traffic Signals." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Establishes a safety motivated amendment to the MUTCD warrant for traffic signals using EB methodologies	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Elvik, R., "Effects on Road Safety of Converting Intersections to Roundabouts: A Review of Evidence From Non-US Studies." Washington, D.C., 82nd Transportation Research Board Annual Meeting 2003, (2003))	Paper discusses a meta-regression analysis approach for 28 studies concerned with converting intersections to roundabouts. The studies selected include both published and unpublished work from locations outside the United States.	More general (and useful) statistics provided in The Handbook of Safety Measures by the same author. Not added to synthesis
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Reference provides a synthesis of various research by topic and comments on overall quality or scope. AMF's are listed as published. Standard error generally not provided so this reference was used to identify other work for further investigation.	Used as a source of other studies. Not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Establishes guidelines for initiatives to reduce aggressive driving. No AMFs provided. Signal coordination listed as a potential strategy. Material not relevant for this subsection.	Not added to synthesis
(Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Kohlman Rabbani, E. R., Hauer, E., and Elefteriadou, L., "Safety Effectiveness of Intersection Left- and Right-Turn Lanes." FHWA-RD-02-089, McLean, Va., Federal Highway Administration, (2002))	Many AMFs provided for left- and right-turn lanes and design features for intersections. Some good references made to other research conducted.	Material not relevant for this section. Not added to synthesis
(Retting, R. A., Chapline, J. F., and Williams, A. F., "Changes in Crash Risk Following Re-timing of Traffic Signal Change Intervals." Accident Analysis and Prevention, Vol. 34, No. 2, Oxford, N.Y., Pergamon Press, (2002) pp. 215-220.)	Paper considers the safety effects of re-timing the yellow and red clearance intervals using ad-hoc vs. ITE methodologies.	Not added to synthesis
(Thomas, G. B. and Smith, D. J., "Effectiveness of Roadway Safety Improvements." Ames, Iowa Department of Transportation, (2001))	Analyzes seven intersection improvement categories in the State of Kansas including new signals, new signals and turn lanes, added turn phasing to existing signals, added turn phasing and turn lanes to existing signals, replace pedestal mount signals with mast arm mounted signals, added turn lanes only and other geometric improvements.	AMFs superseded by other more recent work. Not added to the synthesis
(Lyon, C. and Persaud, B. N., "A Pedestrian Crash Model for Urban 4-Leg Signalized Intersections." London, Ontario, Canada, Canadian Multidisciplinary Road Safety Conference XII, (2001) pp. 1-8.)	Presents safety performance functions for pedestrian crashes at intersections. However, AMFs cannot be derived from the information provided in the paper.	Not added to synthesis
(Bauer, K. M. and Harwood, D. W., "Statistical Models of At-Grade Intersections - Addendum." FHWA-RD-99-094, McLean, Va., Federal Highway Administration, (2000))	Used crash data to develop statistical models of the relationship between traffic crashes and highway geometric elements for at-grade intersections. Multivariate SPFs were developed, but the author concedes that, "they do not appear to be of direct use to practitioners".	Not added to synthesis. Reference suggested by NCHRP 17-18(4).

DOCUMENT	DESCRIPTION	COMMENT
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	AMFs are provided for intersection traffic control based on previous research.	Not added to synthesis. Original research studies referenced where applicable to this section.
(*33*) (Persaud, B., Hauer, E., Retting, R. A., Vallurupalli, R., and Mucsi, K., "Crash Reductions Related to Traffic Signal Removal in Philadelphia." Accident Analysis and Prevention, Vol. 29, No. 6, Oxford, N.Y., Pergamon Press, (1997) pp. 803-810.)	Considers the effects of converting one-way streets in Philadelphia from signal to multi-way stop control.	Added to synthesis.
(Kulmala, R., "Safety at Rural Three- and Four-Arm Junctions: Development and Application of Accident Prediction Models." 233, Espoo, Finland, VTT Technical Research Centre of Finland, (1995))	Before-After study of the safety effectiveness of several geometric design elements at rural three- and four-leg intersections	Not added to synthesis. More relevant to intersection design.
(*34*) (McGee, H. W. and Blankenship, M. R., "NCHRP Report 320: Guidelines for Converting Stop to Yield Control at Intersections." Washington, D.C., Transportation Research Board, National Research Council, (1989))	Study considered a before-after conversion of stop to yield control with a comparison group. Data from the study was used to generate an index of effectiveness and standard error values.	Data from study used to generate AMFs which were added to synthesis.
(Radwan, A. E. and Wing, D., "Safety Effects of Traffic Signal Installations: State of the Art." FHWA/AZ-87/809, Phoenix, Arizona Department of Transportation, (1987))	Synthesis of past research on traffic control at intersections.	Suggested by NCHRP 17-18(4). Not added to synthesis.
(*35*) (Lovell, J. and Hauer, E., "The Safety Effect of Conversion to All-Way Stop Control." Transportation Research Record 1068, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 103-107.)	Considers crash data from San Francisco, Philadelphia, Michigan and Toronto and establishes AMFs for conversion from two-way to all-way stop-control signals.	Added to synthesis.

From the review of references identified, it is apparent that there has been a significant effort over the last 30 years to establish the safety effectiveness of various methods of traffic control at intersections. Many of the studies, however, lack sufficient details to accurately assess the findings from the perspective of safety. More recent efforts report AMFs using state-of-the-art statistical methodologies and provide details on the study data. As a result, for the HSM, more emphasis was placed, where possible, on adopting the latest studies for each type of intersection traffic control.

Treatment: Convert stop control to yield control

As documented in NCHRP Report 320, McGee and Blankenship conducted a review of accidents at intersections where the traffic control was converted from stop-control to yield-control (*34*). The analysis involved a before-after study with comparison group for 141 intersections from 3 cities with a comparison group. The methodology developed for the HSM to generate an index of effectiveness and a corresponding standard error was applied using the data provided in the report. Regression-to-the-mean was a potential factor, and was corrected using an estimate of 0.1. A MCF of 1.5 was also applied. The results show that crashes sharply increase (an AMF of 2.34 with a standard error of 1.151). Unfortunately, no further breakdown by crash type or intersection configuration was possible from the data presented in the study. Specific details are provided in Exhibit 4-43.

Exhibit 4-43: AMF for Stop Control to Yield Control (34)

Study, date	Treatment / element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
McGee and Blankenship, 1989	Stop to Yield Control	Urban/ suburban	All intersection configurations, four-leg, volume not reported	All types, all severities	2.27	1.26

Treatment: Convert two-way to all-way stop-control

The study conducted by Lovell and Hauer in 1986 provides a comprehensive analysis of data from San Francisco, Philadelphia, Michigan and Toronto (*35*). The data provided were sufficient to calculate estimates of the standard error, shown in Exhibit 4-44. The results show a reduction in accidents for all types and severities when intersections are converted from two-way to all-way stop control, but particularly for right angle crashes and crashes involving injuries. All the conversions considered in the study were warranted on the basis of traffic volume patterns, directional splits, and intersection configurations. It is essential that conversions from two-way to all-way STOP-control be used only when the established warrants are met.

The index of effectiveness values adopted for Exhibit 4-44 are as published in the study because the study considered before and after data and controlled regression to the mean effects through the use of likelihood functions.

Standard errors were not provided in the original study. The values shown were established using the adopted HSM procedures. A method correction factor of 1.8 was used to adjust the standard error values to account for the method quality (estimated as medium-high).

Exhibit 4-44: AMF for Conversion from Two-way to All-way Stop Control (35)

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, volume not reported	Right angle, All severities	0.25	0.032
Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, Primarily Urban intersections, volume not reported	Rear-end, All severities	0.82	0.134
Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, Primarily Urban intersections, volume not reported	Left-Turn, All severities	0.71	0.522

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, Primarily Urban intersections, volume not reported	Pedestrian, All severities	0.57	0.150
Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, Primarily Urban intersections, volume not reported	All types, Injury	0.30	0.057
Harwood, Council et al (2000), based on Lovell and Hauer, 1986	Two-way to All-way stop control	Primarily Urban intersections	MUTCD Warrants must be met, Primarily Urban intersections, volume not reported	All types, all severities	0.52	0.038

Note: Conversions from two-way to all-way STOP-control should be used only when the established warrants are met.

Treatment: Convert stop-control to signal

A study published in 2003 by McGee et al. provides AMFs regarding signalization at urban intersections (*32*). The report includes a proposed amendment to the signal warrant provided in the Manual of Uniform Traffic Control Devices (MUTCD). The results show, on average, a decrease in right-angle crashes and an increase in rear-end crashes with an index of effectiveness for all crash types of fatal+injury severity of 0.860 and 0.770 for 3-leg and 4-leg intersections respectively after signalization was installed. Further details are provided below in Exhibit 4-45. The indices of effectiveness values adopted for Exhibit 4-45 are the same as those published in the study. No changes to these values are required because the authors accounted for regression to the mean and traffic volume changes (according to published traffic signal warrant thresholds). A method correction factor of 1.2 (method quality descriptor: high) was used to adjust the standard error values published in the before-after EB study. This value of 1.2 was selected because the methodology used for the study appears to account for all potential confounding factors.

More recently, Davis and Aul used the before-after full Bayes method to estimate the safety impacts of signalizing urban intersections with major road speed limits at least 40 mph (*134*). This study included 17 intersections from the Minnesota Twin Cities metro district that were signalized from 1991 to 1997. AMFs from this study are also included in Exhibit 4-44. A method correction factor of 1.2 (method quality descriptor: high) was used to adjust the standard error values published in the study. Right angle crashes decreased and rear end crashes increased following the installation of signals (the results from McGee et al. could not be combined with thre results from Davis and Aul because McGee et al dealt only with injury crashes). The results from Davis and Aul are recommended for use in the HSM for signalization or urban intersections.

Harkey et al. (*133*), used the before-after EB method to estimate the safety effect of signalizing rural intersections. The study included 6 three-leg intersections and 39 four-leg intersections from Minnesota and California. AMFs from this study are also included in Exhibit 4-44. A method correction factor of 1.2 (method quality descriptor: high) was used to adjust the standard error values published in the study. Here again, right angle crashes decreased and rear-end crashes increased following signalization. The results from Harkey et al. are recommended for use in the HSM for signalization of rural intersections.

Exhibit 4-45: AMF for signalization of intersections

Study, date	Treatment/ element	Setting	Intersection Type, Volume (veh/day)	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
McGee et al., 2003	Convert stop-control to signal	Urban	3-Leg, Major 11,750-42,000 Minor 900-4000	All types, fatal+injury	0.86	0.379
McGee et al., 2003	Convert stop-control to signal	Urban	3-Leg, Major 11,750-42,000 Minor 900-4000	Right-angle, fatal+injury	0.66	0.537
McGee et al., 2003	Convert stop-control to signal	Urban	3-Leg, Major 11,750-42,000 Minor 900-4000	Rear-end, fatal+injury	1.50	0.612
McGee et al., 2003	Convert stop-control to signal	Urban	4-Leg, Major 12,650-22,400 Minor 2400-3625	All types, fatal+injury	0.77	0.268
McGee et al., 2003	Convert stop-control to signal	Urban	4-Leg, Major 12,650-22,400 Minor 2400-3625	Right-angle, fatal+injury	0.33	0.240
McGee et al., 2003	Convert stop-control to signal	Urban	4-Leg, Major 12,650-22,400 Minor 2400-3625	Rear-end, fatal+injury	1.38	0.465
Davis and Aul, 2007	Convert stop-control to signal	Urban, Major Speed Limit at least 40 mph	4-leg	All crashes, all severities	0.95	0.091
Davis and Aul, 2007	Convert stop-control to signal	Urban, Major Speed Limit at least 40 mph	4-leg	Right angle, all severities	0.33	0.056
Davis and Aul, 2007	Convert stop-control to signal	Urban, Major Speed Limit at least 40 mph	4-leg	Rear end, all severities	2.43	0.371
Harkey et al., 2008	Convert stop-control to signal	Rural	3-leg and 4-leg; Major AADT 3,261-29,926; Minor AADT 101-10,300	All types, all severities	0.56	0.030
Harkey et al., 2008	Convert stop-control to signal	Rural	3-leg and 4-leg; Major AADT 3,261-29,926; Minor AADT 101-10,300	Right-angle, all severities	0.23	0.020

Study, date	Treatment/ element	Setting	Intersection Type, Volume (veh/day)	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harkey et al., 2008	Convert stop-control to signal	Rural	3-leg and 4-leg; Major AADT 3,261-29,926; Minor AADT 101-10,300	Left-Turn, all severities	0.40	0.056
Harkey et al., 2008	Convert stop-control to signal	Rural	3-leg and 4-leg; Major AADT 3,261-29,926; Minor AADT 101-10,300	Rear-end, all severities	1.58	0.170

Treatment: Remove an unwarranted signal (one-way streets)

Exhibit 4-46 summarizes the results of a study, based exclusively on data from intersections in Philadelphia, studied by Persaud et al. (*33*). The data for removing signals were collected when the State of Pennsylvania changed the signal warrants and the City of Philadelphia determined that a number of locations that had met the warrants based on past warrants did not meet the warrants after the change in traffic control. Persaud et al. note that these signals are on one-way roadways that are not classified as major arterials but within urban environments. The results, as shown in Exhibit 4-46, indicate a decrease for all crash types when unwarranted signals are removed. There were 199 signals removed on one-way streets and a 71-intersection comparison group was used in the study (*33*).

The index of effectiveness values adopted for Exhibit 4-46 are as published in the study because the authors accounted for regression to the mean and traffic volume changes. A method correction factor of 1.5 was used to adjust the standard error values (confirmed by Hauer). This value of 1.5 was selected because it is a before-after study with large comparison group and several confounding factors have been accounted for using regression analysis techniques.

Exhibit 4-46: AMFs for Removal of Unwarranted Signalization at Intersections (one-way streets in urban areas) (33)

Study, date	Treatment / element	Setting	Intersection Type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Persaud, Hauer et al, 1997	Remove unwarranted signal	Not reported	Unwarranted signals, one-way streets in urban areas, volumes not reported	Right-Angle & Turning, All severities	0.76	0.14
Persaud, Hauer et al, 1997	Remove unwarranted signal	Not reported	Unwarranted signals, one-way streets in urban areas, volumes not reported	Rear-end, All severities	0.71	0.29
Persaud, Hauer et al, 1997	Remove unwarranted signal	Not reported	Unwarranted signals, one-way streets in urban areas, volumes not reported	Pedestrian, All severities	0.82	0.31

Study, date	Treatment / element	Setting	Intersection Type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Persaud, Hauer et al, 1997	Remove unwarranted signal	Not reported	Unwarranted signals, one-way streets in urban areas, volumes not reported	All types, all severities	0.76	0.11

4.2.2. Traffic Signal Operations

Signalized intersections can be controlled using a variety of signal operations, including left-turn phases, right-turn phases, phase and cycle durations, actuated control, advance warning flashers and other operational considerations.

The following sections provide information on the safety effect of each of these operational considerations, as well as the range of options within each. It is expected that the reader is familiar with intersection operations and related terms as described in the Highway Capacity Manual (*11*).

4.2.2.1. Left-Turn Operation

Much research has been conducted on the safety effectiveness of various forms of left-turn control. In recent years, a number of studies have adopted state-of-the-art statistical methodologies to assess the various left-turn options and to identify those characteristics that influence the safety of left-turning traffic.

This section identifies the safety effect of various left-turn operations at signalized intersections including permitted, protected/permitted, permitted/protected and protected left-turn phasing, leading (protected left before through phase) versus lagging (through before protected left phase), and replacing left-turns at intersections with a combined right-turn/u-turn maneuver.

Section 4.1 provides a discussion of the design of left- and right-turn lanes and treatments.

As defined in the Highway Capacity Manual (2000) (*11*):

- Permitted Turn = Left- or right-turns at a signalized intersection that is made against an opposing or conflicting vehicular or pedestrian flow.
- Protected Turn = Left- or right-turns at a signalized intersection that are made with no opposing or conflicting vehicular or pedestrian flow allowed.
- Protected / Permitted = Compound left-turn protection at a signalized intersection that displays the protected phase before the permitted phase.
- Permitted / Protected = Compound left-turn protection that displays the permitted phase before the protected phase.

Where available, information is provided for the environment, traffic volumes, number of opposing lanes, and 3- and 4-leg intersections as well as for various crash types and severities.

Discussion is provided for the following treatments:

- Protected to protected/permitted left-turn operations

- Protected/permitted to permitted/protected left-turn operations
- Leading protected to lagging protected exclusive left-turn operations
- Protected vs. protected/permitted left-turn phasing with the addition of a left-turn lane
- Replacing Direct Left-turns with Right-turn/U-Turn

Exhibit 4-47: Resources examined on the relationship between left-turn operation and safety

DOCUMENT	DESCRIPTION	COMMENT
(*133*) (Harkey, D., et al.,Accident Modification Factors for Traffic Engineering and ITS Improvements, *NCHRP Report* 617, TRB, (2008)	A before-after EB study was conducted to estimate the safety effectiveness of changing the left turn phasing	Added to synthesis
(*134*) (Davis, G.A. and Aul, N., "Safety Effects of Left-Turn Phasing Schemes at High-Speed Intersections", Minnesota Department of Transportation, Report No. MN/RC-2007-03, (2007))	A before-after full Bayes study was conducted to estimate the safety effectiveness of changing the left turn phasing	Added to synthesis
(*130*) Abdel-Aty, M. and Wang, X., Crash Estimation at Signalized Intersections Along Corridors: Analyzing Spatial Effect and Identifying Significant Factors, Transportation Research Record 1953 (2006), pp. 98-111.	Regression models were developed to relate crash frequency with intersection characteristics including left turn phasing	Not added to synthesis. Other studies have used more defensible methods to evaluate left-turn phasing
(*129*) Wang, X. and Abdel-Aty, M., Temporal and Spatial Analysis of Rear-end Crashes at Signalized Intersections, *Accident Analysis and Prevention*, 38 (2006), pp. 1137-1150.	Negative binomial regression models were estimated relating the frequency of rear-end crashes with many intersection and approach characteristics including left-turn phasing	Not added to synthesis. Other studies have used more defensible methods to evaluate left-turn phasing
(*128*) Wang, X., Abdel-Aty, M., and Brady, P., Crash Estimation at Signalized Intersections: Significant Factors and Temporal Effect, *Transportation Research Record* 1953, (2006), pp. 10-20.	Negative binomial regression models were estimated relating the frequency of crashes with many intersection and approach characteristics including left-turn phasing	Not added to synthesis. Other studies have used more defensible methods to evaluate left-turn phasing
(*36*) Lyon, C., Haq, A., Persaud, B., and Kodama, S. T., "Development of Safety Performance Functions for Signalized Intersections in a Large Urban Area and Application to Evaluation of Left Turn Priority Treatment." TRB 2005	Estimated the safety effect of priority left turn treatments at signalized intersections in Toronto.	Added to the synthesis
(*37*) (Hauer, E., "Left Turn Protection, Safety, Delay and Guidelines: A Literature Review." (2004))	Author reviews many studies undertaken between 1975 and 2003, comments on statistical approach, potential biases and findings	Added to the synthesis
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	AMFs provided are from other studies and do not provide standard error values or any information about the study data. Original studies reviewed if applicable.	Not added to the synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	AMFs provided are from other studies and do not provide standard error values or any information about the study data. Original studies reviewed if applicable.	Not added to the synthesis
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003)	AMFs provided are from other references and do not provide standard error values or any information about the study data. Original studies reviewed if applicable.	Not added to the synthesis
(Brehmer, C. L., Kacir, K. C., Noyce, D. A., and Manser, M. P., "NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Evaluates traffic signal head display alternatives for protected/permissive left-turn phasing – not relevant to left-turn phase selection alternatives.	Not added to the synthesis
(*22*) (Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Kohlman Rabbani, E. R., Hauer, E., and Elefteriadou, L., "Safety Effectiveness of Intersection Left- and Right-Turn Lanes." FHWA-RD-02-089, McLean, Va., Federal Highway Administration, (2002))	Study focuses on the addition of turning lanes rather than phasing. Reference is made to AMF for left-turn phasing but there is insufficient information in the data presented to determine standard error.	Added to the synthesis
(Bonneson, J., Middleton, D., Zimmerman, K., Charara, H., and Abbas, M., "Intelligent Detection-Control System for Rural Signalized Intersections." FHWA/TX-03/4022-2, Austin, Texas Department of Transportation, (2002))	Surrogate measures for safety of long distance detection identified along with AMFs developed by others. Applicable to future editions.	Not relevant to this section. Not added to synthesis.
(Thomas, G. B. and Smith, D. J., "Effectiveness of Roadway Safety Improvements." Ames, Iowa Department of Transportation, (2001))	Study focuses mostly on benefit cost ratios for new construction projects, not specifically safety assessments.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(*38*) (Xu, L., "Right Turns Followed by U-Turns Versus Direct Left Turns: A Comparison of Safety Issues." ITE Journal, Vol. 71, No. 11, Washington, D.C., Institute of Transportation Engineers, (2001) pp. 36-43.)	Cross section study reviewed crash experience of 250 sites in FL; included eight-lane, six-lane, and four-lane divided arterials	Suggested by NCHRP 17-18(4). Added to the synthesis
(Sheffer, C. and Janson, B. N., "Accident and Capacity Comparisons of Leading and Lagging Left-turn Signal Phasings." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999) pp. 48-54.)	Compared crash rates between protected-only leading and lagging left-turn phases	Suggested by NCHRP 17-18(4). Included in Hauer's review (2004). Not added to synthesis.
(*39*) (Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999))	Discusses methods for predicting and analyzing safety and traffic operational effects of selected access management techniques.	Qualitative information added to synthesis.
(Tarrall, M. B. and Dixon, K. K., "Conflict Analysis for Double Left-Turn Lanes with Protected-Plus-Permitted Signal Phases." Transportation Research Record 1635, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 1-19.)	Before and after study evaluated the effect of converting a double left-turn lane from protected-plus-permitted to protected only phasing on conflicts, limited to one intersection in metro Atlanta	Suggested by NCHRP 17-18(4). No AMFs. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Shebeeb, O., "Safety and Efficiency for Exclusive Left-Turn Lanes at Signalized Intersections." ITE Journal, Vol. 65, No. July, Washington, D.C., Institute of Transportation Engineers, (1995) pp. 53-59.)	Study evaluated the safety of various left-turn movement phasing at signalized intersections; used crash data. Standard deviations shown in the results are larger than the mean values.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(Carnahan, C. R., Fox, W. C., French, K. A., Hange, W. A., Henderson, J. L., Hook, D. J. P., Imansepahi, A., Khattak, S. S., Paulson, J. D., Resseguie, J. K., Richey, J. M., and Searls, T. D., "Permissive Double Left Turns: Are They Safe?" Washington, D.C., ITE 1995 Compendium of Technical Papers, (1995) pp. 214-218.)	No conclusive AMFs could be determined (i.e. no breakdown of sample sizes and no specific crash rate values).	Suggested by NCHRP 17-18(4). Not added to the synthesis
(Maze, T. H., Henderson, J. L., and Sankar, R., "Impacts on Safety of Left-Turn Treatment at High Speed Signalized Intersections." HR-347, Ames, Iowa Highway Research Board, (1994))	Developed linear regression models from data from 248 intersections. Format of models not reliable.	Not added to the synthesis
(*40*) (Lee, J. C., Wortman, R. H., Hook, D. J., and Poppe, M. J., "Comparative Analysis of Leading and Lagging Left Turns." Phoenix, Arizona Department of Transportation, (1991))	Before and after study on the safety effects of conversion from leading to lagging protected left-turn operation; intersections in 3 areas in AZ	Suggested by NCHRP 17-18(4). Added to the synthesis as reviewed by Hauer

Treatment: Change to protected left-turn phasing

Harkey et al. conducted a before-after EB study based on 12 intersections in Winston-Salem, NC, where permitted or permitted-protected phasing was replaced by protected left turn phasing (*133*). Due to the limited sample of sites in this study, a method correction factor of 1.8 was applied to the standard errors (with a smaller sample there is less confidence in the preciseness of the estimates of the standard errors). Davis and Aul (*134*) conducted a before-after full Bayes study based on 4 intersections in Minnesota: 1 intersection where the minor approach phase was changed from permitted to protected, 2 intersections where the minor approach phase was changed from permitted/protected to protected, and 1 intersection where major approach phasing was changed from permitted-protected to protected. A method correction factor of 1.8 was applied to the standard errors from Davis and Aul (the s_ideal from Davis and Aul were approximate and estimated based on the 95% confidence intervals). Results are shown in Exhibit 4-48. The AMFs from Harkey et al. and Davis and Aul were combined based the procedure outline in the HSM. Overall, the results indicate that introducing left-turn protected phasing virtually eliminates all left-turn crashes on the treated roadway, but the treatment has very little effect on total intersection crashes.

Exhibit 4-48: Change to protected lef t turn phasing

Author, Title	Treatment	Setting Intersection type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harkey et al., 2008	Change from permitted or permitted-protected to protected	Urban, 3 and 4 leg signalized	Not available	Left-turn on treated roadway; all severities	0.014	0.025

Author, Title	Treatment	Setting Intersection type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harkey et al., 2008	Change from permitted or permitted-protected to protected	Urban, 3 and 4 leg signalized	Not available	Total intersection crashes; all severities	0.992	0.126
Davis and Aul, 2007	Change from permitted to protected on minor approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Left turn on minor approach; all severities	0.010	0.020
Davis and Aul, 2007	Change from permitted to protected on minor approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Total intersection crashes; all severities	0.825	0.798
Davis and Aul, 2007	Change from permitted-protected to protected on minor approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Left turn on minor approach; all severities	0.035	0.078
Davis and Aul, 2007	Change from permitted-protected to protected on minor approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Total intersection crashes; all severities	0.990	0.610
Davis and Aul, 2007	Change from permitted-protected to protected on major approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Left turn on major approach; all severities	0.008	0.015
Davis and Aul, 2007	Change from permitted-protected to protected on major approach	Urban 4 leg signalized with major speed limit at least 40 mph	Not available	Total intersection crashes; all severities	0.5808	0.336
Combined AMF for changing left-turn phasing to protected on urban 3 and 4 leg signalized intersections (Harkey et al., 2008, and Davis and Aul, 2007)				Left-turn crashes on treated approach; all severities	0.010	0.011
				Total intersection crashes; all severities	0.941	0.115

Treatment: Permitted to protected/permitted or permitted/protected left-turn phase

Harkey et al. critically reviewed several studies that had tried to evaluate the safety effect of converting from permitted to protected/permitted or permitted/protected phasing. The study by Lyon et al. was identified to be the most defensible. Lyon et al., estimated the safety effect of priority left turn treatments at signalized intersections in Toronto (*36*). SPFs were developed and the statistically defendable empirical Bayes methodology was used to estimate the safety effect of left turn priority treatment. A method correction factor of 1.2 was applied to the standard errors from Lyon et al. The resulting AMFs and standard errors are shown in Exhibit 4-49.(*36*)

Harkey et al. (*133*) also conducted a before-after EB study based on a limited sample of 3 intersections from Winston-Salem, NC, where permitted phasing was replaced by protected phasing. Due to the limited sample of sites in this study, a method correction factor of 1.8 was applied to the standard errors. Davis and Aul used the before-after full Bayes method to study the safety impacts of changing the left-turn phasing on the minor road in four 4-leg intersections from permitted to permitted/protected. Here again, a method correction factor of 1.8 was applied to the standard errors. For left turn injury crashes, the results from Lyon et al. are recommended for inclusion in the HSM, and for total intersection crashes, the results from Harkey et al., 2008, are recommended for inclusing in the HSM (the results from Lyon et al. could not be combined with the results from Harkey et al and Davis and Aul because Lyon et al. dealt only with injury crashes unlike the other two studies).

Exhibit 4-49: Permitted to protected/permitted or permitted/protected left-turn phase

Author, Title	Treatment	Setting Intersection type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lyon, C., et al., 2005 and Harkey et al., 2008	Change permitted to protected/permitted or permitted/protected	Urban Four-leg signalized	Major road 2,978 to 76,892 vpd Minor road 6 to 45,474 vpd	Left-turn injury	0.84	0.022
Harkey et al., 2008	Change permitted to protected/permitted or permitted/protected	Urban Four-leg signalized	Unspecified	Total intersection crashes; All severities	1.00	n/a
Harkey et al., 2008	Change permitted to protected/permitted or permitted/protected	Urban signalized	Not available	Left-turn crashes on treated roadway	0.978	0.499
Davis and Aul, 2007	Changed permitted to permitted/protected on minor approach	Urban signalized (4-leg)	Not available	Left-turn crashes on minor road	0.734	0.984

NOTE: "vpd" = vehicles per day

Treatment: Protected to protected/permitted left-turn operations

Hauer (2004) reviewed information from a study that was originally conducted by Warren et al. in 1985 (*37*). According to Hauer, Warren studies various crash types according to different options of left-turn phasing. The results of this analysis are shown in Exhibit 4-50, which show that converting protected phasing to protected/permitted results in a fairly substantial increase in left-turn crashes while slightly reducing rear-end and other types of crashes. (The definition of "other" crash types is not clearly documented.)

Standard errors in Exhibit 4-50 were calculated by Hauer (*37*). These standard error values were adjusted by a method correction factor of 2.2 (corresponding to a study quality rating of medium-low), based on the methodology applied by Warren et al.

Exhibit 4-50: AMFs for protected to protected-permitted left-turn operations (37)

Author, date	Treatment / element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Hauer, 2004	Protected to Protected-Permitted	Not reported	Not reported	Left-turns, all severities	1.65	1.562
Hauer, 2004	Protected to Protected-Permitted	Not reported	Not reported	Rear End, all severities	0.96	0.484
Hauer, 2004	Protected to Protected-Permitted	Not reported	Not reported	Other, all severities	0.96	0.440
Hauer, 2004	Protected to Protected-Permitted	Not reported	Not reported	All types, injury	1.10	0.550

Treatment: Protected/permitted to permitted/protected left-turn operations

Hauer reviewed information from a 1991 study conducted by Lee et al. (1991) (40) that studied permitted/protected phasing to reduce crashes over protected/permitted (37). The standard errors in Exhibit 4-51 were calculated by Hauer and adjusted by a method correction factor of 2.2 (corresponding to a study quality rating of medium-low), based on the methodology and lack of detail reported. Hauer points out that although the results are not statistically significant, this "does not imply that the estimates are not the most likely ones on the basis of available data" (*37*).

Exhibit 4-51: AMFs for Protected/Permitted to Permitted/Protected Left-turn Operations (37)

Author, date	Treatment/ element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lee et. al, 1991	Protected / Permitted to Permitted / Protected	Not reported	Not reported	Left-turn, all severities	0.67	0.484

Author, date	Treatment/ element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lee et. al, 1991	Protected / Permitted to Permitted / Protected	Not reported	Not reported	All types, all severities	0.87	0.418

Treatment: Leading protected to lagging protected exclusive left-turn operations

When the left-turn phase is exclusively protected (i.e., no permissive left-turn phase), Lee et al. (1991) measured an increase in crashes for lagging exclusive protected phasing over leading exclusive protected phasing (*37*). Standard errors in Exhibit 4-52 were calculated by Hauer, and adjusted by a method correction factor of 2.2 (corresponding to a study quality rating of medium-low). In Hauer's consideration of this study, he points out that although the results are not statistically significant, this "does not imply that the estimates are not the most likely ones on the basis of available data".

Exhibit 4-52: AMFs for Exclusive Leading Protected to Exclusive Lagging Protected (37)

Author, date	Treatment / element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lee et. al, 1991	Exclusive Leading Protected to Exclusive Lagging Protected	Not reported	Not reported	Left-turn, all severities	1.49	1.188
Lee et. al, 1991	Exclusive Leading Protected to Exclusive Lagging Protected	Not reported	Not reported	All types, all severities	1.15	0.418

Treatment: Protected vs. protected/permitted left-turn phasing with the addition of a left-turn lane

Exhibit 4-53 is adapted from Table 54 in the FHWA Report by Harwood et al. (*22*). Although the study focuses on the addition of turning lanes rather than exclusively on differences in phasing, AMFs were developed for different types of left-turn phasing with the addition of new left-turn lanes. However, there is insufficient information in the report to determine standard error of these estimates.

Exhibit 4-53: Comparison of safety effectiveness of added left-turn lanes with protected and protected/permitted signal phasing at urban signalized four-leg intersections (22)

Author, date	Treatment/ element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harwood et al., 2002	Protected left-turn phase with added left-turn lane	Urban	Signalized Four-leg, volumes not reported	All types, all severities	0.90[a]	Unable to calculate
Harwood et al., 2002	Protected/ permitted left-turn phase with added left-turn lane	Urban	Signalized Four-leg, volumes not reported	All types, all severities	0.91[b]	Unable to calculate

NOTE: [a] based on 5 sites
[b] based on 31 sites

Treatment: Replace direct left-turns with right-turn/U-turn

Exhibit 4-54 summarizes the findings of a study conducted by Xu (2001) (*38*). The study offers a cross-sectional comparison of the safety of two egress designs for unsignalized sidestreets and driveways onto divided arterials: direct left-turns; and right-turn followed by U-turn. Xu found that, by closing off the side-street left-turn using directional median openings (effectively forming a T-intersection with a closed median), drivers are forced to turn right and then perform a U-turn on the divided arterial at a downstream location.(*38*)

Xu used similar timeframes for the two samples (direct left-turn locations and right-turn/U-turn locations). This suggests no adjustments to the index of effectiveness are required for volume growth differences. Locations were chosen that had "high ingress and egress volumes" although the actual minor volumes were not reported. Isolated driveways were selected, to minimize interference between multiple driveways. Posted speed limits were between 40 and 55 mph on the arterial road and no parking on the arterial road, arterial road segments were 0.1 to 0.25 miles in length.

Standard error values were calculated based on the number of sites in the study and the duration of observations. Standard errors were then adjusted by a method correction factor of 5 for based on a Low rating and the cross-section study type, due to the lack of information on changes in volumes, driveway volumes, and minimal accounting for confounding factors.

Exhibit 4-54: Replacing Direct Left-turns with Right-turn/U-Turn (38)

Author, date	Treatment/ element	Setting Intersection type	Traffic Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Xu, 2001	Replace direct left-turn with right-turn/U-turn	Unsignalized intersections/ access points on 4-, 6-, and 8-lane divided	Arterial AADT > 34,000 vpd; sidestreet/ access volume unspecified	All crash types All severities	0.80	0.13
				All crash types - PDO	0.89	0.17

Author, date	Treatment/ element	Setting Intersection type	Traffic Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
		arterial		All crash types - Injury and fatality	0.64	0.18
				Rear-end, all severities	0.84	0.22
				Sideswipe, all severities	1.21	0.75
				Angle, all severities	0.64	0.21
		Unsignalized intersections/ access points on 4-lane divided arterial		All crash types - All severities	0.49	0.28
				All types, PDO	0.56	0.37
				All types, Injury+fatal	0.38	0.39
		Unsignalized intersections/ access points on 6-lane divided arterial		All crash types - All severities	0.86	0.15
				All types, PDO	0.95	0.20
				All types, Injury+fatal	0.69	0.21
				rear-end, all severities	0.91	0.25
				Sideswipe, all severities	1.33	0.92
				Angle, all severities	0.67	0.25
		Unsignalized intersections/ access points on 8-lane divided arterial		All crash types - All severities	0.89	0.67
				All types, PDO	0.97	0.86
				All types, Injury+fatal	0.73	1.04

Based on three studies summarized by Gluck et al. (pg 100) (*39*), providing u-turns as alternatives to direct left-turns, specifically the "Michigan U", may improve safety. The Michigan U-turn design has evolved since the 1970s. The first study showed directional crossovers have lower average intersection-related accident rates compared to bidirectional crossovers, for total crashes and for injury crashes. The second study of Grand River Avenue in Detroit showed a 61 percent reduction in the average number of accidents yer year on the 0.43 mile section over 5 years. Angle accidents had the greatest reduction (96%), followed by sideswipe (61%) and rear-end (17%) accidents.(*39*) The third study of 123 segments of boulevard containing 226 mi of highway stratified segments by bidirectional or directional crossovers, then by the number of signals per segment. The results indicated that on divided highway sections without traffic signals, directional U-turn median crossovers had a 14% higher accident rate than segments with bidirectional median crossovers. The method used to accident rate was accidents per 100 million vehicle miles. As the density of traffic signals increased, divided highways with directional crossovers had decreasing relative accident rates compared to divided highways with bidirectional crossovers.(*39*) Published data was insufficient to determine an AMF.

The above study findings from Xu and Gluck et al., are assumed to apply to this indirect left-turn treatment at intersections (or at least to high-volume driveways that function as intersections). Liu et al. studied a related, but somewhat different issue – closing left turns from driveways (*145*). The authors attempted to address the safety effect of the separation distance between driveway exits and downstream U-turn locations. Negative binomial regression models were estimated to relate total number of crashes and total number of target crashes (target crashes included crashes directly related to the indirect left-turn treatment) and site characteristics including traffic volume, separation distance and whether a U-turn bay was provided at a signalized intersection (where cross traffic would be present) versus a median opening (where cross traffic would not be present). The models indicated that "separation distances significantly impact the safety of the street segments between the driveways and the downstream U-turn locations". The models showed that a "10% increase in the separation distance will result in a 3.3% decrease in total crashes and a 4.5% decrease in crashes which are related with right turns followed by U-turns". The results from the regression models were also compared with the average number of crashes (involving left-turns from driveways) that occurred at 32 three-leg unsignalized intersections where direct left-turns from driveways were allowed. The comparisons indicated that if the separation distance was less than 175 feet, right turns followed by U-turns may actually produce more crashes compared to direct left-turns. However, for separation distances longer than 175 feet, the right U-turn combination will produce fewer crashes if the U turns can be made from a median opening (i.e., locations without cross traffic). For separation distances longer than 500 feet, the right-turn U combination will produce fewer crashes compared to direct left turns regardless of whether the U turn can be made from a median opening or signalized intersection. Since this study was based on a treatment of driveway left-turns, it is difficult to know whether the findings apply to the same treatment at intersections. If applicable, the implied guidance is that if the right U-turn treatment is applied to an intersection, the median opening U-turn location should be located at least 175 feet from the intersection.

4.2.2.2. Right-Turn Operation

Substantial research work has been undertaken since the early 1980s to evaluate the safety implications for right-turn-on-red. The studies of this time considered data collected during the previous decade when many eastern states adopted RTOR policies. Since then, few opportunities have emerged that would provide the necessary data to conduct similar studies.

As mentioned, this section also provides information on the safety effect of right-turn operations at signalized intersections. Crashes, especially pedestrian and bicyclist crashes, at signalized intersections where right-turns are permitted during the red signal indication are considered against "area wide right-turn-on-red" prohibitions.

This section is divided into two major components, right-turn-on-red operations at traffic signals and right-turn channelization. Other safety effects addressed in this section include free slip lanes (channelization) at a signalized intersection.

Section 4.1 provides a discussion of the design of left- and right-turn lanes and treatments. Section 4.3 discusses the impact of intersection operations on pedestrian and cyclist safety.

Exhibit 4-55: Resources examined on the relationship between right-turn-on-red and safety

DOCUMENT	DESCRIPTION	COMMENT
(*133*) (Harkey, D., et al.,Accident Modification Factors for Traffic Engineering and ITS Improvements, *NCHRP Report* 617, TRB, (2008)	Expert panel critical review of studies related to right-turn-on-red	Added to synthesis
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities. Refers to key findings from previous research as "expected effectiveness".	Not added to the synthesis
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook that summarizes the effects of a wide range of safety measures	Added to synthesis
(*41*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians including the effect on pedestrian safety of right-turn-on-red operation	Suggested by NCHRP 17-18(4). Added to the synthesis
(*42*) (Lord, D., "Synthesis on the Safety of Right Turn on Red in the United States and Canada." Washington, D.C., 82nd Transportation Research Board Annual Meeting, (2003))	Reviews various studies	Suggested by NCHRP 17-18(4). Added to the synthesis
(*43*) (Retting, R. A., Nitzburg, M. S., Farmer, C. M., and Knoblauch, R. L., "Field Evaluation of Two Methods for Restricting Right Turn on Red to Promote Pedestrian Safety." ITE Journal, Vol. 72, No. 1, Washington, D.C., Institute of Transportation Engineers, (2002) pp. 32-36.)	Evaluated the safety effect on pedestrians of RTOR restrictions at 15 intersections in Arlington, VA; Evaluation criteria for comparing the two methods includes drivers stopping at stop lines, drivers turning right on red, drivers turning right on red without stopping. – Any crash statistics provided were very broad based in nature.	Suggested by NCHRP 17-18(4). Added to the synthesis
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Provides a synthesis of results from many studies for rural intersections. No specific AMFs provided for RTOR.	Not added to the synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Huang, H., "The Effects of No Turn on Red/Yield to Peds Variable Message Signs on Motorist and Pedestrian Behavior." Florida Department of Transportation, (2000))	The study investigated motorist and pedestrian behavior at variable message signs that displayed NO TURN ON RED or YIELD TO PEDS No crash data presented in the study.	Not added to the synthesis
(Hunter, W. W., "Evaluation of a Combined Bicycle Lane/Right Turn Lane in Eugene, Oregon." FHWA-RD-00-151, McLean, Va., Federal Highway Administration, (2000))	The study compared conflicts and maneuvers at two intersections. Possibly related to intersection design, but no crash data provided. "No conflicts were recorded at either intersection." – page 14.	Not added to the synthesis
(Davis, G. A. and Adams, D., "Identifying High-Hazard Sites for Older Drivers." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 201-207.)	Study applies EB methodologies for 102 sites in Minnesota to identify high-hazard sites for older drivers. The breakdown of accident types does not explicitly consider RTOR or channelization	Not added to the synthesis
(Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	Evaluated the safety impact of permitting right-turn-on-red movements, used total crashes and fatal crashes, crashes with other motor vehicle and pedestrian crashes. No AMFs generated.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(*44*) (Zegeer, C. V. and Cynecki, M. J., "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." Transportation Research Record 1059, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 24-34.)	Field evaluation of the effect of seven RTOR countermeasures on pedestrian safety; used conflicts and violations as surrogates; 34 intersections in 6 U.S. cities	Suggested by NCHRP 17-18(4). Added to the synthesis
(*45*) (Clark, J. E., Maghsoodloo, S., and Brown, D. B., "Public Good Relative to Right-Turn-on-Red in South Carolina and Alabama." Transportation Research Record 926, Washington, D.C., Transportation Research Board, National Research Council, (1983) pp. 24-31.)	Before and after study of the effect of RTOR laws on crashes at intersections in SC and AL	Suggested by NCHRP 17-18(4). Added to the synthesis
(*46*) (Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M., "The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents." Journal of Safety Research, Vol. 13, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 45-55.)	Evaluated the effect of a "Western" version of RTOR on pedestrian and bicycle crashes with motor vehicles; sites in NY, WI, OH, and LA	Suggested by NCHRP 17-18(4). Added to the synthesis
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Publication provides a synthesis of previous studies and percentages of RTOR crashes in various data samples. No AMFs or supporting data provided	Not added to the synthesis

Many of the earlier studies (i.e., 1980's) conducted to assess the safety of permitting right-turn-on-red also published the data collected in the study. In many cases and as described below, these data were used to generate more statistically defensible AMFs and the associated standard error values.

Treatment: Permit Right-Turn-On-Red (RTOR)

Exhibit 4-56 shows that permitting RTOR increases pedestrian crashes based on a study by Preusser et al. (*46*). Exhibit 4-56 displays the results of individual data sets supplied by 4 different jurisdictions (New York State (except New York City), Wisconsin, Ohio, and New Orleans) as well as the result of combining the AMFs and standard errors together. The index of effectiveness values (AMFs) were calculated from the data supplied by Preusser et al.

Preusser et al. indicate the mean values shown have been adjusted to account for seasonal differences but does not indicate if volume increases were accounted for. However, no further adjustments were made on the AMFs calculated from the data.

A method correction factor of 2.2 was used to adjust the standard error values calculated from the data, based on the use of accident frequencies and non-EB methodologies.

Exhibit 4-56: AMFs for Pedestrian Crashes for Permitting Right-Turn-On-Red (46)

Author, date	Treatment/ element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New York State)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.429	0.243
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Wisconsin)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	2.075	0.512
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Ohio)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.574	0.306
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New Orleans)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.813	0.881
				Combined	**1.57**	**0.18**

The study by Preusser also included information that allows for the calculation of AMFs for bicycle crashes (*46*). Again, AMF values with standard errors were calculated from the data provided in the Preusser report, based on data from three different jurisdictions (New York State (except New York City), Wisconsin, and Ohio). The standard error values have been multiplied with a method correction factor of 2.2 (i.e., medium low rating) to account for the study methodology. The results are shown in Exhibit 4-57.

The results show that RTOR has a negative safety effect on bicycle crashes at signalized intersections.

Exhibit 4-57: AMFs for Bicycle Crashes for Permitting Right-Turn-On-Red (46)

Author, date	Treatment / element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New York State)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.820	0.315
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Wisconsin)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.726	0.524
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Ohio)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.798	0.525
				Combined	**1.80**	**0.24**

Elvik and Vaa provide AMFs for RTOR based on U.S. studies in the "Handbook of Safety Measures, by the severity of right-turn crashes (pg 508) (*5*). Standard error calculated based on 95% confidence intervals provided by Elvik and Vaa were then multiplied by a method correction factor of 1.8 (medium-high rating) based on the meta-analysis approach used.

Elvik and Vaa's findings indicate that the adoption of RTOR has a negative impact on the safety of right-turns, both for injury and property damage only crashes (Exhibit 4-58).

Exhibit 4-58: AMFs for Right-turn Crashes for Permitting Right-Turn-On-Red (5)

Author, date	Treatment / element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Permit right-turn-on-red	Not reported	Signalized Intersections, volume not reported	Right-turn Crashes, Injury	1.60	0.090
Elvik and Vaa, 2004	Permit right-turn-on-red	Not reported	Signalized Intersections, volume not reported	Right-turn Crashes, PDO	1.10	0.009

Although not explicitly presented in their report, Clark et al. provide sufficient data and information for the studies conducted in South Carolina and Alabama to be able to determine AMFs and standard errors (*45*). The data, interpreted for AMFs, reflects a naïve before-after study without explicit consideration of volume changes. The calculated standard errors were adjusted by a method correction factor of 2.2 (medium low rating). The results are shown in Exhibit 4-59 and are valuable in that they reflect all crashes occurring at signalized intersections, not just right-turning conflicts or crashes. The data are listed for each state separately and then combined. In each case, an increase in crashes after permitting RTOR was evident based on the data.

Exhibit 4-59: AMFs for All Signalized Intersection Crashes for Permitting Right-Turn-On-Red (45)

Author, date	Treatment / element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Clark et al., 1983	Permit right-turn-on-red	Not reported (South Carolina)	Signalized Intersections, volume not reported	All Crashes, All Severities	1.13	0.021
Clark et al., 1983	Permit right-turn-on-red	Not reported (Alabama)	Signalized Intersections, volume not reported	All Crashes, All Severities	1.05	0.011
				Combined	**1.067**	**0.010**

The various studies reviewed above have similar conclusions. The data from these studies consistently shows that permitting right-turn-on-red at a jurisdictional level has a negative effect on safety.

Additional information on restricting and permitting right-turn-on-red is provided in Section 4.3 on pedestrian and bicyclist safety at intersections.

Discussion: Restrict Right-Turn-On-Red (RTOR)

Very little quantitative crash data were found on the analysis of right-turn-on-red restrictions. A 2008 study examined earlier study data to develop an AMF for restricting/prohibiting RTOR. Studies in 1986 and 2002 considered the compliance of drivers to signing restrictions. In their 1986 study, Zegeer et al. investigated violation rates for NO TURN ON RED (NTOR) and the resulting pedestrian-vehicle conflicts (*44*). In a reference to this study, Campbell et al. note that Zeeger and Cynecki found that “3.7 percent of all right-turning motorists at RTOR-prohibited intersections violate the NTOR signs. However, approximately 21 percent violate the NTOR signs if given an opportunity (e.g. first in line at the intersection with no pedestrians in front of them and no vehicle coming from the left)” (*41*).

Harkey et al. (*133*) critically reviewed studies related to restricting/prohibiting right-turn-on-red and concluded that the Clark, et al., study noted in the section above was the most pertinent. That expert panel assumed that most of the intersections in the Clark study were 4-leg locations with all approaches allowing RTOR. Taking the inverse of the Clark findings, they suggest that the AMF for *prohibiting* RTOR is = $(0.984)^n$, where “n” is the number of treated approaches. This formation indicates that crashes are reduced as the number of RTOR legs are reduced.

In a study by Retting et al. (2002), two methods of restricting RTOR at urban intersections were assessed (*43*):

- Traffic signals restricting RTOR at specified times, and

- Highly visible traffic signs restricting RTOR when pedestrians are present.

The study was conducted at 15 signalized intersections in Arlington, Virginia. Evaluation criteria for comparing the two methods included drivers stopping at stop lines, drivers turning right on red, drivers turning right on red without stopping.

Retting concludes with the following remark, “At intersections with frequent pedestrian activity and where RTOR restrictions are approved to promote pedestrian safety, preference should be given to installing traffic signs prohibiting RTOR during specified hours tailored to pedestrian activity rather than signs giving drivers discretion to determine whether pedestrians are present” (*43*).

Additional information on restricting and permitting right-turn-on-red is provided in Section 4.3 on pedestrian and bicyclist safety at intersections.

4.2.2.3. Signal Timing, Clearance Intervals, and Cycle Length

This section contains information on the safety effects of timing parameters of a signalized intersection including the length of the yellow interval, the use of an all-red interval, and the use of split phases.

As defined in the Highway Capacity Manual (2000) (*11*):

- Cycle = A complete sequence of signal indications
- Cycle length = the total time for a signal to complete one cycle
- Interval = a period of time in which all traffic signal indications remain constant.
- Split Phase = temporal separation of the two approaches from the same roadway.

Related issues such as: pedestrian crossing times (lead/lag, pedestrian only phase) and “scramble” phases in Section4.3, and red light running in Section 4.2.8. Signal coordination will be discussed in Section 4.2.8 in a future edition.

Exhibit 4-60: Resources examined for the relationship between signal phases and safety.

DOCUMENT	DESCRIPTION	COMMENT
(*47*) (Souleyrette, R. R., O'Brien, M. M., McDonald, T., Preston, H., and Storm, R., "Effectiveness of All-Red Clearance Interval on Intersection Crashes." MN/RC-2004-26, St. Paul, Minnesota Department of Transportation, (2004))	Authors provide several methodologies to assess all-red clearance intervals for safety. Data from the study used to generate AMFs and standard error values.	Added to the synthesis
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Provides a strategy for implementing integrated safety programs. Some samples of “expected effectiveness” are provided. One such description adopted for split phases	Added to the synthesis
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	All red intervals recommended, but no specific studies sited that can assist in producing AMFs.	Not added to the synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Reference provides a synthesis of various research by topic and comments on overall quality or scope. AMFs are listed as published. Where applicable, original study reports were reviewed.	Not added to the synthesis.
(Bonneson, J. A. and Son, H. J., "Prediction of Expected Red-Light-Running Frequency at Urban Intersections." Transportation Research Record, No. 1830, Washington, D.C., Transportation Research Board, National Research Council, (2003) pp. 38-47.)	Study establishes relationships between duration of yellow intervals and occurrence of red-light running. No AMFs provided.	Not added to the synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Provides a strategy for implementing integrated safety programs. Some samples of "expected effectiveness" are provided, but none that deal with signal timing parameters.	Not added to the synthesis.
(*48*) (Retting, R. A., Chapline, J. F., and Williams, A. F., "Changes in Crash Risk Following Re-timing of Traffic Signal Change Intervals." Accident Analysis and Prevention, Vol. 34, No. 2, Oxford, N.Y., Pergamon Press, (2002) pp. 215-220.)	Evaluated the crash effects of modifying the change interval; 122 intersections with a random before and after with control; examined crashes	Suggested by NCHRP 17-18(4). Added to the synthesis
(Datta, T. K., Schattler, K., and Datta, S., "Red Light Violations and Crashes at Urban Intersections." Washington, D.C., 79th Transportation Research Board Annual Meeting, (2000))	Crude Before and after analysis to evaluate the effect of an all-red-interval on crashes; conducted in Detroit, MI for 3 intersections. Does not account for volume changes or RTM.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(Retting, R. A. and Greene, M., "Influence of Traffic Signal Timing on Red-Light Running and Potential Vehicle Conflicts at Urban Intersections." Transportation Research Record 1595, Washington, D.C., Transportation Research Board, National Research Council, (1997))	Before and after study on the effect on safety of increased change intervals; used potential conflicts as surrogates; 10 urban intersections. However, study used potential conflicts, not actual conflicts or crashes.	Suggested by NCHRP 17-18(4). Not added to the synthesis.
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)	Linear regression models developed to establish a relationship between inter-green period and accident rates. However, models not intended to accurately predict rates.	Not added to the synthesis.
(Roper, B. A., Fricker, J. D., Montgomery, R. E., and Sinha, K. C., "The Effects of the All-Red Clearance Interval on Accident Rates in Indiana." TE 1991 Compendium of Technical Papers, Washington, D.C., ITE 1991 Compendium of Technical Papers, (1991) pp. 361-365.)	The study analyzes crashes at 25 treatment intersections and 25 comparison intersections for a period 2-year before and 5-years after the installation of all-red clearance intervals. However, no study data were provided and the findings of the study were inconclusive.	Suggested by NCHRP 17-18(4). Not added to the synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Bhesania, R. R., "Impact of Mast-Mounted Signal Heads on Accident Reduction." ITE Journal, Vol. 61, No. 10, Washington, D.C., Institute of Transportation Engineers, (1991) pp. 25-29.)	Simple before and after study of mast-mounted signal heads and 1-second of all-red at 6 signalized intersections. However, cannot separate new hardware from signal timing.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(Zador, P., Stein, H., Shapiro, S., and Tarnoff, P., "Effect of Signal Timing on Traffic Flow and Crashes at Signalized Intersections." Transportation Research Record 1010, Washington, D.C., Transportation Research Board, National Research Council, (1984) pp. 1-8.)	Comparative analysis of traffic signal change interval timing and daytime crashes at 91 intersections throughout the US	Suggested by NCHRP 17-18(4). Insufficient information to draw conclusions. Not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Provides a synthesis of various research studies conducted prior to 1982, but does not present original data or an opportunity to calculate any new AMFs.	Not added to the synthesis.
(Dawson, R. F. and Oppenlander, J. C., "General Design." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 11, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Report provides crash statistics for various environments, states, and facilities. Also provides high level safety data by major type of facility improvement. Insufficient information provided for descriptions of treatments and on the particulars of the data (i.e. durations for before/after periods, etc.)	Not added to the synthesis.

Treatment: Update inter-green intervals to ITE Standards

Retting et al. provide the most recent information regarding signal change intervals and safety (*48*). The study examines the effect of re-timing 40 signals using the ITE Proposed Recommended Practice for Determining Vehicle Change Intervals (1985). Another 56 signals were selected as a comparison group. Random assignment of the sites to experimental and control groups reduces the possible biases due to regression to the mean.

The data presented in the study was used to determine AMFs and standard errors in accordance with the procedures documented in Table 9.8, page 125 of (*50*). Standard error values as shown were adjusted with a method correction factor of 1.2 (in accordance with HSM procedures for B/A studies with comparison groups, rated high). The results are shown below in Exhibit 4-61.

Yellow change intervals at the treatment sites ranged from 3 to 4 seconds in the before period and 2.6 to 5.4 seconds in the after period. Red clearance intervals ranged from 2 to 3 seconds in the before period and 1.1 to 6.5 seconds in the after period.

Exhibit 4-61: AMFs for Modifying Clearance Intervals at Traffic Signals

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	All types and severities	0.91	0.10

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Rear-end, all severities	1.11	0.20
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Right angle, all severities	0.94	0.21
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Pedestrian / Bicyclist, all severities	0.61	0.19
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	All types, Injury	0.87	0.11
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Rear-end, Injury	1.06	0.21
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Right angle, Injury	1.30	0.26
Retting, Champline & Williams, 2002	Retiming signal change intervals to ITE standards	Not reported	4-Leg Signalized Intersections, volume not reported	Pedestrian / Bicyclist, Injury	0.61	0.19

Discussion: Installation of an All-Red Clearance Interval

Souleyrette et al. considers the safety implications of providing an all-red interval at traffic signals in Minneapolis (*47*). Two methodologies were described in the paper: a) a cross-section study was used for 38 sites with all-red clearance intervals and 38 sites without; b) a before-after study of 22 treatment sites with a comparison group of 47 sites. The combined results of both methodologies indicate an overall 47% increase in accidents. Data were insufficient to develop AMFs.

These findings contradict those of previous research. In the background research documented by Souleyrette et al., fewer crashes were observed in the study by Datta et al. (2000) although all red intervals were introduced along with alterations to the yellow intervals. In the study by Roper et al. (1991), no significant difference was cited (using two distinct comparisons) before and after the implementation of an all red interval (as cited in (*47*)).

In consideration of the Souleyrette et al. report in light of the inconclusive findings from previous studies, it is suggested that more research be conducted that can establish more conclusively the overall affects of an all-red interval to safety.

Discussion: Implement split phases

Although no conclusive findings were identified, Antonucci et al. provide some general information on the effectiveness of split phases in "A Guide for Addressing Accidents at Signalized Intersections", NCHRP 500 Volume 12 (*4*). Reference is made to Page V-11 which provides a general description of the effects on safety of implementing split phase operations:

"Though studies have not conclusively proven that implementation of split phases reduces fatalities and severe injuries at signalized intersections, the elimination of conflicts can logically be expected to reduce crashes. Using split phases to separate opposing traffic can be expected to greatly reduce the sideswipe, rear-end, and angle conflicts and the accidents associated with the geometric situation that contributes to the conflicts between the opposing vehicles. The effectiveness in reducing crashes involving left-turning vehicles should be similar to that of adding a protected-only left-turn phase."

4.2.2.4. Actuated Control

This section would ideally contain information on the safety effect of various types of phase operations (i.e., fully actuated, semi-actuated, and pre-timed). Currently, there is limited information available regarding the safety effect of actuated intersection control. There is a need to quantify the safety impact of various forms of signal actuation on all crash types at different intersection types and environments.

As defined in the Highway Capacity Manual (2000) (*11*):

- Fully actuated control = a signal operation in which vehicle detectors at each approach to the intersection control the occurrence and length of every phase.
- Pre-timed control = a signal control in which the cycle length, phase plan and phase times are preset to repeat continuously.
- Semi-actuated control = a signal control in which some approaches (typically on the minor street) have detectors, and some of the approaches (typically on the major street) have no detectors.

Exhibit 4-62: Resources examined on the relationship between actuated controls and safety

DOCUMENT	DESCRIPTION	COMMENT
(Mohamedshah, Y., Chen, L., and F.M.Council, "Association of Selected Intersection Factors With Red-Light-Running Crashes." FHWA-RD-00-112, McLean, Va., Federal Highway Administration, (2000))	Before/After study at 10 intersections (20 approaches) to establish red-light running trends vs. yellow intervals, back plates on signal heads, flow rates/cycle lengths.	Not added to the synthesis.
(*51*) (Bamfo, J. K. and Hauer, E., "Which is Safer in terms of Right-Angle Vehicle Accidents? Fixed-time or Vehicle-actuated Signal Control." Toronto, Ontario, Canada, Canadian Multidisciplinary Road Safety Conference X, (1997) pp. 352-360.)	Multivariate models were established to determine the relationship between right-turn crashes on approaches with vehicle actuated or pretimed control.	Added to the synthesis

Only qualitative evidence of the safety affects of various forms of phase operations where found in the various references reviewed.

Discussion: Vehicle actuated approaches

In a 1997 cross section study of data taken at 306 intersections in Hamilton-Wentworth, Bamfo et al. determined that there is a general increase in the number of right-angle crashes for approaches with fixed time (FT) control over approaches with vehicle actuated (VA) control (*51*). The database consisted of 46 three-leg intersections, 6 with VA and 40 with FT, and 260 four-leg intersections, 22 with VA and 238 with FT.

As the sample size of right-angle crashes for the vehicle actuated approaches was small, the overall precision of the findings were a noted concern by the authors… "However, inasmuch as the number of approaches and the total number of accidents at approaches with the VA control is small, sound conclusive statements may not be made of these observations. Nonetheless, it is suggestive that for similar traffic flows, the safety of a representative FT approach from the study database is about 15% higher than that of a representative VA approach" (pg 358) (*51*). Because of the limited precision, no standard error values were established.

4.2.2.5. Detector Placement and Signal Control on High Speed Approaches [Future Edition]

The onset of the change interval at a signalized intersection can be timed so as to minimize the likelihood that a motorist will be a distance from the intersection where they may be indecisive about whether to stop or proceed through the intersection, i.e., in the "dilemma zone". Traffic detectors can be placed strategically to determine the optimum onset of the change interval.

In future editions of the HSM, the safety of minimizing the occurrence of "dilemma zone" decisions will be addressed here. This section may identify the safety effect of detector placement on high-speed approaches to signalized intersections. Detector placement on approach to roundabouts with signals may also be addressed here. Potential resources are listed in Exhibit 4-63.

Exhibit 4-63: Potential resources on the relationship between detector placement and signal control and safety

DOCUMENT
(Bonneson, JA, and McCoy, PT, "Traffic Detector Designs For Isolated Intersections " ITE Journal, Vol. 66, No. 8, 1996)

4.2.2.6. Advance Warning Flashers and Warning Beacons

An advance warning flasher (AWF) is a traffic control device that provides drivers with advance information on the status of a downstream traffic signal. Advance warning flashers may be linked to the signal timing mechanism or operate continuously.

This section discusses the effect of advance warning flashers on the safety of the intersection.

Exhibit 4-64: Resources examined on the relationship between advanced warning flashers and safety

DOCUMENT	DESCRIPTION	COMMENT
(*52*) (Sayed, T., Vahidi, H., and Rodriguez, F., "Advance Warning Flashers: Do They Improve Safety?" Transportation Research Record, No. 1692, Washington, D.C., Transportation Research Board, National Research Council, (1999) pp. 30-38.)	Model parameters are provided along with Accident Reduction indications for each site. It is possible to develop AMFs and standard error values from these data; however, the standard errors are very large and were not adopted for inclusion into the synthesis.	Suggested by NCHRP 17-18(4). Added to the synthesis but not AMFs
(Farraher, B. A., Weinholzer, R., and Kowsji, M. P., "The Effect of Advanced Warning Flashers on Red Light Running - A Study Using Motion Imaging Recording System Technology at Trunk Highway 169 and Pioneer Trail in Bloomington, Minnesota." Las Vegas, Nev., Proc. 69th Institute of Transportation Enginners Annual Meeting, (1999))	Study considers red-light violations with and without AWFs by vehicle type, time of day, approaching speeds. No crash data provided.	Suggested by NCHRP 17-18(4). Not added to the synthesis.
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)	Linear regression models developed to establish a relationship between sites with and without AWFs. However, models not intended to accurately predict rates.	Not added to the synthesis.
(Box, P. C., "Intersections." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 4, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Provides a synthesis of studies conducted for advanced warning flashers (amongst other studies). However the report is dated and has been superseded by more recent work	Not added to the synthesis.

In 1999, Sayed et al. published a study that considered the crash histories of intersections with and without Responsive Advanced Warning Flashers (AWFs) (*52*). A total of 25 sites without AWFs and 81 sites with AWFs were selected for analysis. The AWFs under consideration consisted of illuminated, rectangular signs with 200 mm yellow flashing beacons in each of the upper corners. The flashing interval commenced (one second on, one second off) prior to the onset of the yellow at the traffic signal.

Regression analysis was conducted using three different approaches:

1. Separate model approach – separate GLIM models developed for AWF and non-AWF intersections.
2. Single Model approach – a single accident prediction model to represent all of the intersections in the data sample.
3. Separate "unforced" models – the development of two separate accident prediction models for AWF and non-AWF locations (as in Method 2) without, however the "forcing" of any of the parameters.

Sayed et al. provide graphical comparisons of expected total accidents by traffic volumes for various minor road AADTs (Exhibit 4-65).

Sayed et al. note:

- "When minor street traffic volumes are low (i.e., AADT at 3,000), AWF benefits are limited if not negligible. Here it is observed that as the major street traffic volumes increase, AWF locations are correlated with increasing accident frequency relative to the non-AWF locations."

- "When minor street traffic volumes are moderate (i.e., AADT at 8,000), AWF benefits varied by the major street traffic volumes. Here it is observed that where the major street AADT is below 35,000 vehicles per day, the AWF locations have a lower accident frequency relative to the non-AWF locations."
- "When the minor street traffic volumes are high (i.e., AADT at 18,000), AWF locations are consistently associated with lower accident frequency in comparison to the non-AWF locations, and regardless of the major street traffic volumes. For the Total model, the "cross-over" point was found to be a minor road AADT of approximately 13,000 – meaning that when the minor road volume exceeded this value the AWF locations have consistent lower accident frequencies."

Exhibit 4-65: Comparison of expected total accidents by traffic volume (Figure 2 of (52))

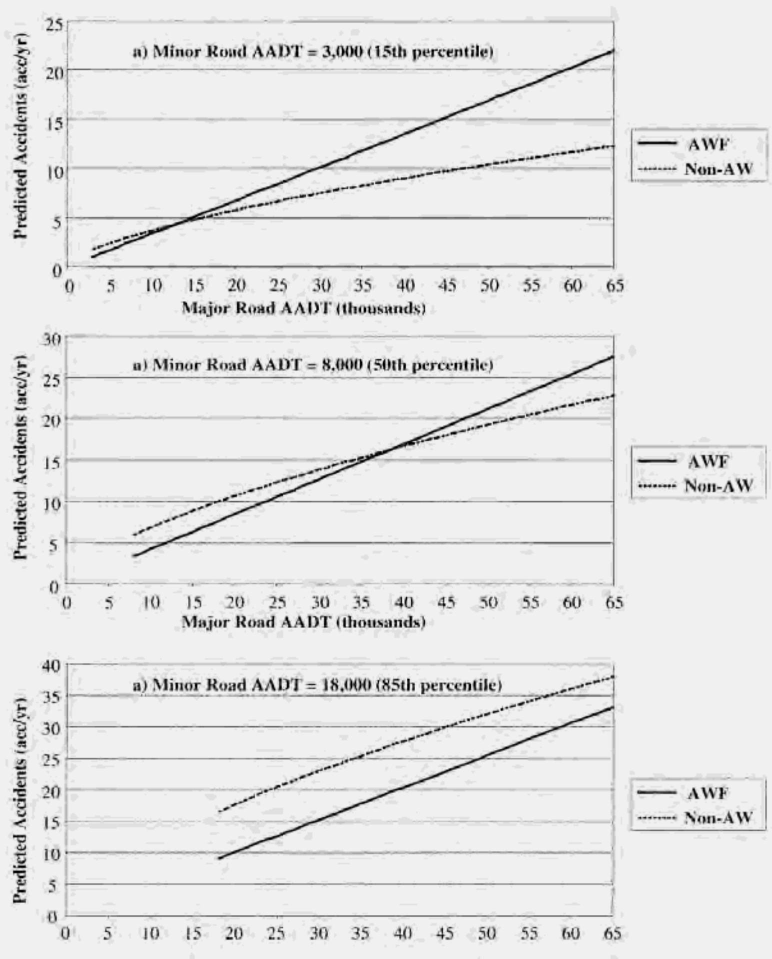


Figure 2 Comparison of Expected Total Accidents By Traffic Volume

Gibby et al. came to the same conclusion about the effectiveness of advance warning treatments for intersections when they concluded that "advance warning flashers (AWFs) seem to improve the safety" of approaches to high-speed isolated signalized intersections. Although there was insufficient information to derive indices of effectiveness and their corresponding standard errors, based on a comparison of accident rates between sites comprised of rural, isolated signalized intersections with high speed approaches with AWFs and similar sites without AWFs, Gibby et al. suggested that "an approach may experience as much as a 50 percent reduction in approach accident rates after installation of an AWF". Using a similar approach to examine the effectiveness of advance warning signs with no flashers (AWSs), the researchers concluded that AWSs have "little effect on approach accident rates" (*53*).

4.2.2.7. Other Operational Considerations

This section contains information on the safety effect of other traffic signal operational considerations such as the use of flashing signal operation during low-volume periods, sometimes referred to as "night-flash" operations.

Flashing traffic signal operation can be used during low volume conditions to minimize delay at a signalized intersection. The section provides some discussion of the trends between crashes at intersections during flashing operation against full signal operations.

There is a need to quantify the safety impact of flashing signal operations in low volume conditions. Future editions of the HSM may contain additional traffic signal operations.

Exhibit 4-66: Resources examined on the relationship between various signal operational considerations and safety

DOCUMENT	DESCRIPTION	COMMENT
(*133*) (Harkey et al., "Accident Modification Factors for Traffic Engineering and ITS Improvements", NCHRP Report 617, (2008)	Before-after EB studies were conducted using data from Winston-Salem to evaluate the safety of different treatments including night-flash operation.	Added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Reference provides a synthesis of various research by topic and comments on overall quality or scope. AMFs are listed as published. Where applicable, original study reports were reviewed.	Not added to the synthesis
(Polanis, S. F., "Do 12" Signal Lenses Reduce Angle Crashes?" Washington, D.C., Institute of Transportation Engineers 68th Annual Meeting, (1998))	Describes the results of a before and after study on the effect of 12 inch signal lenses on crashes at 38 signals in Winston-Salem, NC. However, no independent results provided for night-flash operations.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(Sayed, T., Abdelwahab, W., and Nepomuceno, J., "Safety Evaluation of Alternative Signal Head Design." Transportation Research Record 1635, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 140-146.)	Empircal Bayes before and after crash analysis of the effect of increased signal head size at 10 urban intersections in British Columbia. However, this report does not consider flashing signal operations.	Suggested by NCHRP 17-18(4). Not added to the synthesis
(*54*) (Barbaresso, J. C., "Relative Accident Impacts of Traffic Control Strategies During Low-Volume Night Time Periods." ITE Journal, Vol. 57, No. 8, Washington, D.C., Institute of Transportation Engineers, (1987) pp. 41-46.)	Before and after study evaluated the effect on crashes of flashing operation at six 4-legged intersections; also conducted comparative analysis of crashes at intersections by signal operation	Suggested by NCHRP 17-18(4). Added to the synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Short, M. S., Woelfl, G. A., and Chang, C. J., "Effects of Traffic Signal Installation On Accidents." Accident Analysis and Prevention, Vol. 14, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 135-145.)	Considers 31 recently signalized intersections in Milwaukee. However, the author concludes "that the change in PDOE accidents is associated with some phenomena independent of either flash or normal operation alone."	Not added to the synthesis.

Few studies appear to have been conducted on the safety effects of operating traffic signals in a flashing condition during nighttime or low volume periods. One study that did consider the effects of flashing operations was published in the ITE Journal by Barbaresso in 1987 (*54*). The study considers 6 signalized intersections selected for available crash data for 3-years before and 3-years after flashing nighttime operations was eliminated. It also considers a cross-section study of 82 additional intersections.

Although the data provided in the study report does not allow for the generation of AMFs and standard errors, the author notes that "eliminating flashing signal operation at the four-legged arterial intersections analyzed in this study should result in a reduction of 0.13 right-angle accidents per year-hour eliminated" (pg 44) (*54*). The method of site selection is not clear; therefore regression-to-mean is a potential confounder of these results.

Barbaresso also finds "The results of this study indicate that right-angle accidents are significantly overrepresented at four-legged arterial intersections when signals are in a flashing mode during nighttime hours. T-type intersections and arterial-collector intersections, where signals flash part time, experienced significantly fewer right-angle accidents than the other intersection types analyzed" (pg 45) (*54*).

Harkey et al., 2008 (*133*), conducted a before-after EB study using data from 12 signalized intersections in Winston Salem, NC, where night time flash operation was replaced by steady operation (see Exhibit 4-67). This study was rated medium high due to limited sample and an MCF of 1.8 was used to modify the standard errors. The results indicated about a 35% reduction in nighttime angle and total nighttime crashes following the replacement of flashing operation.

Exhibit 4-67: Replacing Night-Time Flashing Operation with Steady Operation

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Harkey et al., 2008	Replace Night-Time Flash with Steady Operation	Urban	3-leg and 4-Leg Signalized Intersections, volume not reported	Nighttime angle; all severities	0.659	0.324
Harkey et al., 2008	Replace Night-Time Flash with Steady Operation	Urban	3-leg and 4-Leg Signalized Intersections, volume not reported	All Nighttime; all severities	0.651	0.261

4.2.3. Signs

Traffic signs are typically classified as one of three categories: Regulatory signs; Warning signs and Guide Signs. As defined in the Manual on Uniform Traffic Control Devices (*17*), Regulatory signs provide notice of traffic laws or regulations, warning signs give notice of a situation that might not be readily apparent, and guide signs show route designations, destinations, directions, distances, services, points of interest, and other geographical, recreational or cultural information. While MUTCD provides the standards, as well as guidance and options necessary for signing within the right-of-way of all types of highways open to public travel, many agencies supplement the information contained in this manual with their own guidelines and standards. The MUTCD does not specify the conditions (traffic, road geometry, etc.) under which the signs are to be used.

This section examines the safety effects of signage at, and in advance of signalized and unsignalized intersections and roundabouts. The discussion in this section excludes any consideration for yield and stop signs intersections and also any signs along roadway segments since these topics are addressed in Sections 4.2.1 and 3.2.

Given that a large number of studies that investigate the safety impacts of signs at intersections are related to pedestrian crosswalks, readers may also refer to Section 4.3. In terms of signage within work zones, the reader is directed to Section 6.2.

Exhibit 4-68: Resources examined to investigate the safety effect of signs at intersections or roundabouts

DOCUMENT	DESCRIPTION	COMMENT
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Study provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities.	Added to synthesis. Anecdotal evidence of signage safety effectiveness found. No quantitative information provided.
(*13*) (Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report provides engineering, planning, education, and policy guidance for accommodating the needs of older drivers in order to reduce crashes and fatalities	Added to synthesis. Anecdotal evidence of the safety effectiveness of signs found. No quantitative information provided.
(*10*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Reference is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections.	Added to synthesis. Anecdotal evidence of the safety effectiveness of signs at intersections found. No quantitative information provided.
(Van Houten, R., Malenfant, J. E., and McCusker, D., "Advance Yield Markings: Reducing Motor Vehicle-Pedestrian Conflicts at Multilane Crosswalks with Uncontrolled Approach." Transportation Research Record, No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 69-74.)	Evaluated the effect of advance yield markings and a symbol sign on pedestrian safety at intersections; used conflicts, pedestrian and motorist behavior as surrogate.	Not added to synthesis since more relevant to Sections 3.3 and 4.3 (Pedestrian and Bicycle Safety at Intersections).

DOCUMENT	DESCRIPTION	COMMENT
(*23*) (Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways through a review of previous studies.	Added to synthesis. Some anecdotal evidence of speed reductions resulting from signs at horizontal curves but no quantitative information provided about safety impacts.
(Huang, H., "The Effects of No Turn on Red/Yield to Peds Variable Message Signs on Motorist and Pedestrian Behavior." Florida Department of Transportation, (2000))	The study investigated effectiveness of variable message signs in changing motorist and pedestrian behavior at intersections. Focus on vehicle-pedestrian conflicts involving vehicles turning right on red	Not added to synthesis since more relevant to Pedestrian and Bicyclist Safety at Intersections.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Reviews existing research and attempts to provide guidelines on highway engineering improvements that would help older drivers and pedestrians.	Not added to synthesis. No discussion on safety impacts of signs.
(Retting, R. A., Van Houten, R., Malenfant, L., Van Houten, J., and Farmer, C. M., "Special Signs and Pavement Markings Improve Pedestrian Safety." ITE Journal, Vol. 66, No. 12, Washington, D.C., Institute of Transportation Engineers, (1996) pp. 28-35.)	Before-after study investigated the effectiveness of special signs and pavement markings used to prompt pedestrians to look for turning vehicles at intersections.	Not added to synthesis since more relevant to Pedestrian and Bicycle Safety at Intersections.
(Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995),Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))	The report traces the evolution of roundabout design in the UK up to 1993 and provides a brief synopsis of some previous safety research studies in Chapter 7 (page 136).	Not added to synthesis. No quantitative or qualitative evidence of crash reductions related to signs found.
(*55*) (Brich, S. C. and Cottrell Jr, B. H., "Guidelines for the Use of No U-Turn and No-Left Turn Signs." VTRC 95-R5, Richmond, Virginia Department of Transportation, (1994))	Naïve before and after study that evaluated the effect of No U-Turn and No Left-Turn signs on crash rates at 8 signalized intersections	Reference suggested by NCHRP 17-18(4). Added to synthesis. t and s values related to “No Left Turn” and “No U-Turn” signs calculated using available accident data
(Kuciemba, S. R. and Cirillo, J. A., "Safety Effectiveness of Highway Design Features: Volume V - Intersections." FHWA-RD-91-048, Washington, D.C., Federal Highway Administration, (1992))	Report briefly discusses nine studies (1972 to 1988) of the relationship between intersection design/operations and safety	Not added to synthesis. No information on signs.
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)	Cross-sectional analysis comparing accident rates for high-speed, isolated signalized intersections.	Added to Section on Advance warning flashers.

DOCUMENT	DESCRIPTION	COMMENT
(Upchurch, J. E., "Guidelines for Use of Sign Control at Intersections to Reduce Energy Consumption." ITE Journal, Vol. 53, No. 1, Washington, D.C., Institute of Transportation Engineers, (1983) pp. 22-34.)	Discussion on warrants for traffic signals at intersections	Not added to synthesis. No information on safety effectiveness of signs
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis study reviewing 17 safety research areas	Not added to synthesis. No material on the safety effectiveness of signs at intersections or roundabouts.
(*1*) (Box, P. C., "Intersections." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 4, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reference reviews studies relating safety to elements of intersections, including geometric layout, left turn lanes, traffic controls, signing, and turn restrictions among others.	Added to synthesis. Some quantitative data found on effectiveness of overhead and roadside directional signs, and advance warning signs with flashers but insufficient data to calculate t and s values.

From the review of studies, there appears to be few studies that have attempted to quantify the safety impacts of signs at intersections or roundabouts other than those used to draw attention to pedestrian crossings. Of those references that were reviewed, only one presented any information on the quantified safety impacts of signs at intersections. The remaining references were limited to discussions on safety using anecdotal based information.

Treatment: Install “No Left Turn” and “No U-Turn” signs

Brich and Cottrell reviewed a study by Shoaf (1967) that examined the safety effectiveness of prohibiting left-turns and U-turns through the installation of “No Left Turn” or “No U-Turn” signs at intersections on urban and suburban arterials and found that this particular treatment reduced the number of left-turn accidents by 47% to 63% (*55*). Although no other details were provided about that particular study, results from a similar analysis carried out by the researchers themselves appear to concur with these findings. Using a simple before-after approach, Brich and Cottrell reported a 59% reduction in left-turn and u-turn accidents and a 62% reduction in total accidents following the implementation of this change in traffic operations and the installation of “No U-Turn” and/or “No Left Turn” signs at intersections and median crossovers. The intersections and median crossovers studied had an entering ADT volume range of 19,435 to 42,000 veh/day. It is unclear from the reference if the intersections examined were signalized or unsignalized.

Indices of effectiveness and standard error values shown in Exhibit 4-69 were calculated using the reported number of crashes and the ratio of before-after duration. These results were assigned a medium-low rating based on the study quality, and a method correction factor of 2.2 was applied to the s ideal calculated to account for this. In addition, the AMFs have been adjusted to account for the known changes in traffic volume that occurred at the treatment sites during the study by dividing by 1.09 (increase in traffic of 9%).

Although changes in traffic volumes were provided in the study, it should be noted that the researchers did not take into account the possibility of accident migration or spillover to adjacent intersections or median crossovers that were not studied.

Exhibit 4-69: Safety effects of prohibiting left-turns and/or U-turns by installing "No Left Turn" and/or "No U-Turn" signs (55)

Author, date	Treatment / Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Brich and Cottrell (1994)	Prohibit left-turns with "No Left Turn" sign	Urban and suburban arterial	Three- and Four-leg intersections and median crossovers Entering AADT 19,435 to 42,000 vpd	Left-turn, All severities	0.36	0.2
				All intersection crashes, All severities	0.32	0.1
	Prohibit left-turns and U-turns with "No Left Turn" and "No U-Turn" signs			Left-turn and U-Turn crashes, All severities	0.23	0.2
				All intersection crashes, All severities	0.28	0.2

Discussion: Advance warning signs with beacons

The more cues there are to the presence of an intersection and the further away these cues can be seen, the more readily a driver will detect the presence of the intersection in time to perform whatever maneuver may be required there. The less expected the intersection is, the more cues are needed and the more visible the cues should be. Although there was insufficient data and evidence to reach a definitive, quantitative conclusion on its safety impacts, the general consensus among researchers in the references reviewed was that advance warning signs, particularly when used in conjunction with flashers, are effective in improving the overall safety of intersections.

Box reported that a study by Smith and Vostrez (1964) had examined the safety effectiveness of static flashing beacons in conjunction with advance warning signs, and found that the use of the treatments resulted in a 20% reduction in accidents (*1*). Antonucci et al. added that some crashes such as rear-end or angle accidents at signalized intersections may occur because drivers are unaware of the presence of an intersection or are unable to see the traffic control device in time to comply. The researchers suggested that installing advance warning signs or upgrading signs can alert drivers to the presence of an intersection (*4*). Potts et al. added that advanced warning signs can "help reduce confusion and perception/reaction time at existing or potentially hazardous conditions on or adjacent to the roadways", particularly for older drivers (*13*).

AMFs could not be developed for advance warning signs or flashers based on the available literature.

Discussion: Impact of advance warning signs on surrogate safety measures

In terms of the effects advance warning signs have on surrogate measures such as speed, Fitzpatrick et al. reported on the findings from a study by Lyles (1980) and stated that lighted warning signs were found to be more effective than more traditional unlighted warning signs in reducing vehicle speeds in the vicinity of rural intersections (*23*). The treatments were also found to be more effective in increasing driver awareness of both the signs and the conditions at the intersection. No information as to how the researchers arrived at this conclusion was provided.

Discussion: Advance guide signs

None of the studies examined provided any quantitative evidence of safety improvements resulting from the use of advance guide signs. Although intuitively, one expects that this treatment will improve safety since it enables drivers to detect the presence of an approaching intersection, findings from a previous research study appears to show mixed and inconclusive results.

For instance, Box reviewed a study by Stevens (1958) that investigated the safety effectiveness of directional signing upstream of intersections in reducing sideswipe accidents and found that overhead directional signs reduced sideswipe accident rates from 2.6 per million vehicles the year before installation, to 1.7 the first year after, and then to 0.9 for both the second and third years after. Conversely, the installation of roadside directional signs resulted in increases in sideswipe accident rates from 0.9 to 3.2 per million vehicles after the installation of the treatment. The road classes and traffic volumes for the sites examined in the study were not reported. Although it is unclear from the study whether direct comparisons can or should be made since no further information about the signs were provided (i.e. the location of the overhead and roadside signs relative to the intersection, font sizes, etc.), Box concluded by suggesting that overhead directional signs are more effective in reducing sideswipe accidents compared to roadside directional signs because they were more visible to drivers who had to make lane changes upstream of an intersection (*1*).

Neuman et al. stated that the use of advance guide signs such as lane assignment signing, in tandem with appropriate pavement markings, can reduce accidents caused by driver indecision (*10*). Potts et al. added that providing advance guide signs may also reduce crashes involving older drivers because these treatments provide older drivers with additional time to make necessary lane changes and route selection decisions (*13*).

AMFs could not be developed for advance guide signs based on the available literature.

4.2.4. Delineation

Delineation has long been considered as an essential element for providing effective guidance to drivers on highways. Delineation typically refers to any method of defining the roadway operating area for drivers and may include delineation devices such as pavement markings made from a variety of marking materials, raised pavement markers (RPMs), pavement markers, and post-mounted delineators (PMDs) (*56*). The MUTCD adds that markings on highways have important functions in providing guidance and information for the road user.

Major marking types include pavement and curb markings, object markers, delineators, colored pavements, barricades, channelizing devices and islands. In some cases, markings are used to supplement other traffic control devices such as signs, signals and other markings. In other instances, markings are used alone to effectively convey regulations, guidance, or warnings in ways not obtainable by the use of other devices (*17*).

In the case of delineation devices such as post-mounted delineators, the MUTCD states that they can be particularly beneficial at locations where the alignment might be confusing or unexpected, such as at lane reduction transitions and curves (*17*). Delineators are effective guidance devices at night and during adverse weather. An important advantage of delineators in certain locations is that they remain visible when the roadway is wet or snow covered since they are required to be retroreflective and mounted above the roadway surface and along the side of the roadway in a series to indicate the alignment. In terms of retroreflectivity requirements, the MUTCD stipulates that delineators are required to have retroreflective elements with a minimum dimension of 3 in (75 mm) and be capable of retroreflecting light under normal atmospheric conditions from a distance of 1,000 ft (300 m) when illuminated by the high beams of standard automobile lights (*17*).

The MUTCD adds that the visibility of pavement markings can be obscured by snow, debris, and water on or adjacent to the markings. The visibility can also be compromised since the durability of the pavement marking is affected by weather, its material properties, traffic volumes and location, and subsequently degrades (*17*).

The MUTCD presents standard ways of conveying information to the driver through the design, color, pattern and width of the pavement marking. For example, yellow lines separate traffic flowing in opposing directions, whereas white lines denote traffic flowing in the same direction (*56*). A double line indicates maximum or special restrictions; a solid line discourages or prohibits crossing (depending on the specific application); a broken line indicates a permitted condition; and a dotted line provides guidance (*17*). The reader is directed to the MUTCD for further detailed standards related to color, pattern, and width of pavement markings.

This section investigates the safety effects of the different delineation practices typically used to regulate, warn or provide guidance to drivers at or in close proximity to intersections, and excludes any examination of road segments.

For the safety effect of delineation treatments on road segments, refer to Chapter 3. Given that a large number of studies investigating the safety impacts of pavement markings at intersections are related to crosswalks, readers may also refer to Section 4.3.

Exhibit 4-70: Resources examined to investigate the safety effect of delineation at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*136*) (Gross, F., Jagannathan, R., Lyon, C., and Eccles, K., "Safety Effectiveness of STOP AHEAD Pavement Markings", Presented at the 87th Annual Meeting of the Transportation Research Board, 2008)	Used a before-after EB approach to evaluate the safety impact of stop-ahead pavement markings.	Added to synthesis.
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "A Guide for Addressing Accidents at Signalized Intersections." NCHRP 500 Volume 12, Washington, D.C., Transportation Research Board, National Research Council, (2004))	Study provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities.	Added to synthesis. Anecdotal evidence of delineation safety effectiveness found. No quantitative information provided.
(*13*) (Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "A Guide for Addressing Accidents Involving Older Drivers." NCHRP 500 Volume 9, Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report provides engineering, planning, education, and policy guidance for accommodating the needs of older drivers in order to reduce crashes and fatalities	Added to synthesis. Anecdotal evidence of delineation safety effectiveness found. No quantitative information provided.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Not added to synthesis. No relevant material found on pavement markings at intersections.
(*10*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "A Guide for Addressing Unsignalized Intersection Accidents." NCHRP Report 500 Volume 5, Washington, D.C., Transportation Research Board, National Research Council, (2003))	Reference is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections.	Added to synthesis. Anecdotal evidence of pavement marking safety effectiveness found. No quantitative information provided.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "A Guide for Addressing Unsignalized Intersection Accidents." NCHRP Report 500 Volume 5, Washington, D.C., Transportation Research Board, National Research Council, (2003))	Reference is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections.	Not added to synthesis. No quantitative information provided.
(Van Houten, R., Malenfant, J. E., and McCusker, D., "Advance Yield Markings: Reducing Motor Vehicle-Pedestrian Conflicts at Multilane Crosswalks with Uncontrolled Approach." No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 69-74.)	Evaluated the effect of advance yield markings and a symbol sign on pedestrian safety at intersections; used pedestrian and motorist behavior as surrogate.	Reference suggested by NCHRP 17-18(4). Not added to synthesis since more relevant to Pedestrian and Bicycle Safety at Intersections.
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Summarizes various studies on pedestrian crossing treatments at uncontrolled intersections, signalized intersections, and mid-block signals.	Reference suggested by NCHRP 17-18(4). Not added to synthesis since more relevant to Pedestrian and Bicycle Safety at Intersections.

DOCUMENT	DESCRIPTION	COMMENT
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "Accident Mitigation Guide for Congested Rural Two-Lane Highways." 440, Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study investigated low-cost safety and operational improvements for two-lane and three-lane roadways through a review of previous studies.	Not added to synthesis. Brief mention of pavement markings at intersections but no qualitative or quantitative information provided about safety impacts.
(Storm, R., "Pavement Markings and Incident Reduction." Ames, Iowa, 2000 MTC Transportation Scholars Conference, (2000) pp. 152-162.)	Reference identifies the areas where pavement markings are most likely to reduce crashes and focuses on the application of pavement markings in three areas: horizontal curvature, turning movements, and pedestrian crosswalks.	Reference suggested by NCHRP 17-18(4). Not added to synthesis since more relevant to Pedestrian and Bicycle Safety at Intersections.
(Persaud, B. N., Parker, M., Wilde, G., and IBI Group, "Safety, Speed & Speed Management: A Canadian Review." Ottawa, Ontario, Canada, Transport Canada, (1997))	The study reviewed the relationships between safety, speed limits and the impact of various traffic control devices on speeds and crashes	Not added to synthesis since the one study identified to be relevant (Griffin and Reinhardt, 1996) was reviewed first-hand and added to the synthesis.
(Retting, R. A., Van Houten, R., Malenfant, L., Van Houten, J., and Farmer, C. M., "Special Signs and Pavement Markings Improve Pedestrian Safety." Vol. 66, No. 12, Washington, D.C., Institute of Transportation Engineers, (1996) pp. 28-35.)	Before-after study investigated the effectiveness of special signs and pavement markings used to prompt pedestrians to look for turning vehicles at intersections. Study measures changes in pedestrian behavior and conflicts not crashes.	Not reviewed since information from reference was already included in the critical review reported in (Storm, 2000).
(*57*) (Griffin, L. I. and Reinhardt, R. N., "A Review of Two Innovative Pavement Patterns that Have Been Developed to Reduce Traffic Speeds and Crashes." Washington, D.C., AAA Foundation for Traffic Safety, (1996c))	Study reviews the effectiveness of converging chevron pattern road markings and transverse bar pattern markings.	Added to synthesis. t and s values calculated using accident reduction percentages and 95% percentile confidence intervals as reported in reference (p. 39-41).
(*58*,*28*) (Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995), Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))	The report traces the evolution of roundabout design in the UK up to 1993 and provides a brief synopsis of some previous safety research studies in Chapter 6 (page 136).	Added to synthesis. Quantitative evidence of crash reduction found although there are insufficient data to calculate t and s values.
(Zegeer, C. V. and Cynecki, M. J., "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 24-34.)	Field evaluation of the effect of advanced stop lines (pavement marking) on pedestrian safety; used conflicts and violations as surrogates; 34 intersections in 6 U.S. cities.	Reference suggested by NCHRP 17-18(4). Not added to synthesis since more relevant to Pedestrian and Bicycle Safety at Intersections.

From the review of studies identified previously, it appears that few researchers have attempted to quantify the safety impacts of delineation treatments other than pavement markings at intersections or roundabouts. The large majority of safety studies related to delineation treatments at intersections or roundabouts typically deal with pavement markings and not the other forms of delineation such as object markers and post-mounted delineators. A number of studies dealt with pedestrian crosswalk markings, and therefore are discussed in their relevant sections.

It is difficult to study and to quantify the safety impacts of specific types of pavement markings at intersections and roundabouts given that the use of such treatments is often regulated through the MUTCD. This subsequently minimizes the chances of finding sites with similar characteristics (i.e. traffic volumes, etc.) and yet have different pavement markings or none altogether. One study which did develop AMFs for one type of pavement marking is described in the following section.

Treatment: Stop Ahead Pavement Markings

Providing Stop Ahead pavement markings can alert drivers to the presence of an intersection. These markings can be especially useful in rural areas at unsignalized intersections with patterns of crashes related to drivers not being aware of the intersection. Gross et al. conducted a before-after EB study using data from approaches to 17 stop controlled intersections in Arkansas and Maryland (*136*). Due to the limited sample size and other study limitations, an MCF of 1.8 was applied to the standard errors (see Exhibit 4-73). The pavement markings seem to have been effective in reducing total intersection crashes, total injury crashes, and rear-end crashes. They seem to be more effective at 3-legged intersections and in all way stop controlled intersections.

Exhibit 4-71: Introducing Stop Ahead Pavement Markings

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 and 4 leg stop controlled intersections	Right angle; all severities	1.036	0.326
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 and 4 leg stop controlled intersections	Rear-end; all severities	0.710	0.324
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 and 4 leg stop controlled intersections	Injury crashes	0.784	0.216
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 and 4 leg stop controlled intersections	Total crashes; all severities	0.689	0.144
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 leg stop controlled	Injury crashes	0.453	0.295
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	4 leg stop controlled	Injury crashes	0.881	0.270

Study, date	Treatment/ element	Setting	Intersection type, Volume	Accident type, severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	All way stop controlled	Injury crashes	0.577	0.268
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	One-way stop control or two-way stop control	Injury crashes	0.923	0.315
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	3 leg stop controlled	Total crashes; all severities	0.399	0.202
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	4 leg stop controlled	Total crashes; all severities	0.770	0.178
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	All way stop controlled	Total crashes; all severities	0.441	0.164
Gross et al., 2008	Introduce stop ahead pavement markings	Predominantly rural (15 rural and 2 urban)	One-way stop control or two-way stop control	Total crashes; all severities	0.872	0.220

Discussion: Post-mounted delineators at intersections

Antonucci et al. investigated a number of strategies designed to improve safety at signalized intersections and through a review of an ongoing study being conducted in Winston-Salem, North Carolina, found that removing small right-turn triangular channelizing islands and using flexible delineators along the gore stripe to provide positive guidance to drivers turning right, potentially reduces right-turn rear-end crashes. This particular treatment is expected to prevent situations where right-turning drivers approaching the intersection only detect the channelizing islands at the very last minute, stop suddenly and consequently face a high risk of being rear-ended. Although the "after" study had not been completed at the time the reference was written, preliminary findings suggest that right-turn rear-end crashes are "becoming less common" (*4*).

Discussion: Delineators and older drivers

Potts et al. (*13*) discussed several strategies to accommodate the needs of older drivers in order to reduce crashes and fatalities. According to the researchers, increasing the awareness of roadway elements among older drivers through the use of pavement markings and delineation "should improve overall safety" since this heightened awareness will "quicken older drivers' reaction times when conflicts occur". However, the effectiveness of this strategy has not been quantified.

Although all these studies contain some type of anecdotal information suggesting some reduction in crashes due to the implementation of delineation treatments at intersections or roundabouts, of the studies examined, none provide the data and quantitative evidence necessary to reach a definitive, quantitative conclusion on its safety impacts.

Treatment: Transverse bar pavement marking at roundabout approaches

According to Griffin and Reinhardt, transverse bar pavement markings are most often used at approaches to roundabouts that are preceded by long stretches of highway on which drivers could habituate to higher speeds (*57*). Other applications of this particular type of pavement marking have been located at the approaches to intersections, horizontal curves, construction areas, and freeway off-ramps.

Griffin and Reinhardt reviewed a number of studies that examined the impact of such treatments on crashes and identified two studies (Havell, 1983 and Helliar-Symons, 1981, as cited by (*57*)) that provided the quantitative data necessary to calculate AMFs and standard error values. Of the these two studies, only the AMFs and corresponding standard error values derived from the Helliar-Symons study are included in this synthesis for HSM because upon reviewing the study, Griffin and Reinhardt remarked that the crash data used in the study by Havell (1983) were “often ambiguous or inexact”.

In the review of the study by Helliar-Symons (1981), Griffin and Reinhardt re-analyzed data available to determine the safety effect of transverse bar markings consisting of strips of yellow thermoplastic material 0.6m (2 ft) in width, applied on the approaches to roundabouts. Only crashes on or within one kilometer (0.62 miles) of the roundabout involving vehicles that had crossed the treatment approach and had been judged to be speed-related were considered. Results from the study are summarized in Exhibit 4-72. The road classes and traffic volumes at the sites examined were not reported. This study was considered to be of medium-low quality (simple before after study with 2 years before and 2 years after data) and the standard error values have been multiplied with a method correction factor of 2.2 to account for this.

Exhibit 4-72: Safety effect of transverse bar pavement markings on roundabout approaches

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Total Speed-related, Injury Crashes	0.43	0.19
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related, Single vehicle crashes	0.53	0.30
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related Serious Injury Crashes	0.26	0.28
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related Slight Injury Crashes	0.48	0.24
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related, Daytime crashes	0.34	0.18

Author, date	Treatment / Element	Setting	Intersection type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related, Wet surface crashes	0.32	0.23
Griffin and Reinhardt, 1996	Transverse bar markings	Not specified	Not specified	Speed-related, Dry Surface crashes	0.55	0.33

Discussion: Pavement markings at roundabouts

Brown (*28*) reviewed a number of studies on the safety impacts of pavement markings at roundabout approaches (Green, 1973; Helliar-Symons, 1981) and within the roundabout (Yee and Bell, 1986). Although there were insufficient data to estimate the actual index of safety effectiveness of such a treatment, the study by Green (1973) reported that a change from single 8 in (200mm) by 3 ft (0.91m) wide broken white yield line markings at roundabout approaches to 18 in wide markings supplemented with yield signs resulted in 18% fewer injury accidents compared to the national average. It is unclear how this national average was derived, and caution should be exercised using the site accident reduction given the likelihood of confounding factors. Yee and Bell (1986) examined the safety impacts of concentric lane markings and found that while there was a reduction in speed, the markings did not "sufficiently reduce accidents". The degree to which the treatment reduced vehicle speeds was not reported. The study by Helliar-Symons on the safety impacts of transverse bar pavement markings was previously discussed as part of the review done by Griffin and Reinhardt. (*57*).

Discussion: Improved or more conspicuous pavement markings at unsignalized intersections

In the study by Neuman et al. (*10*), the researchers discuss various strategies to improve the safety at unsignalized intersections and state that the use of delineation (and enhanced signing) "should improve safety at the intersection" because drivers will be more alert to potential vehicles on the cross streets. However, they add that that the effectiveness of this strategy has not been quantified. Another treatment reviewed by Neuman et al. was the use of a stop bar (or a wider stop bar where one already exists) on minor-road approaches at intersections. According to the researchers, this treatment is expected to be "especially effective" when applied on approaches where conditions allow the stop bar to be seen by an approaching driver at a significant distance from the intersection. Once again, the effectiveness of such a treatment has not been quantified.

Discussion: Extended edgelines and centerlines through median openings and unsignalized intersections of divided highways

Neuman et al. also discussed the use of dashed markings (extended left edgelines) across median openings at unsignalized divided highway intersections and deemed this treatment to be particularly appropriate for intersections with patterns of rear-end, right-angle, or turning accidents (*10*). The use of this particular treatment will make it less likely for drivers of vehicles waiting in the median roadway for an appropriate gap, to stop in a position with a portion of their vehicle encroaching on the through roadway. Neuman et al. suggested that this strategy "should assist in reducing accidents" between vehicles using the median roadway and through traffic but found that its effectiveness has not been satisfactorily quantified. In addition, the use of double yellow centerlines at the median openings of divided highways at intersections were also discussed and although the safety effectiveness of this particular strategy has also not been quantified, the researchers stated that the presence of a double yellow centerline "should" minimize side-by-side queuing of vehicles and angled stopping on the median roadway, thereby reducing driver confusion.

Discussion: Lane assignment markings

According to Neuman et al. (*10*), at complex intersections, drivers sometimes face difficulties in determining the appropriate lane from which to perform certain maneuvers and this can potentially lead to accidents. Neuman et al. suggested that the use of lane assignment markings can reduce accidents caused by driver indecision or error such as when a driver performs an unexpected maneuver from an inappropriate lane (e.g., a vehicle making a left-turn from a through lane). However, as with the other pavement markings treatments discussed in this particular reference, the effectiveness of lane assignment markings has not been quantified.

Antonucci et al. (*4*) appear to be in agreement when they stated that pavement markings can be a low-cost solution to guide through vehicles traveling within an intersection with substantial deflection. They added that dashed lines similar to those used to delineate left-turn paths are appropriate for the delineation of the through path. No quantitative analysis was conducted to verify this.

4.2.5. Speed Limits [Future Edition]

In future editions of the HSM, this section may contain discussion on the safety impact of speed limits on intersection approaches in a variety of settings. Treatments such as variable speed limits, lowering the speed limit, and the use of differential speed limits may be included. This section will build on the discussions of speed in other sections of the HSM. Potential resources are listed in Exhibit 4-73.

Exhibit 4-73: Potential resources on the relationship between speed limits and safety at intersections

DOCUMENT
(Johansson, C., Garder, P., and Leden, L., "The Effect of Change in Code on Safety and Mobility for Children and Elderly as Pedestrians at Marked Crosswalks - A Case Study Comparing Sweden to Finland." Washington, D.C., 83rd Transportation Research Board Annual Meeting, (2004))
(Persaud, B. N., Retting, R. A., Garder, P. E., and Lord, D., "Observational Before-After Study of the Safety Effect of U.S. Roundabout Conversions Using the Empirical Bayes Method." Transportation Research Record, No. 1751, Washington, D.C., Transportation Research Board, National Research Council, (2001))
(Weiss, A. and Schifer, J. L., "Assessment of Variable Speed Limit Implementation Issues." NCHRP 3-59, Washington, D.C., Transportation Research Board, National Research Council, (2001))
(Vogt, A., "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized." FHWA-RD-99-128, McLean, Va., Federal Highway Administration, (1999))
(Hummel, T., "Dutch Pedestrian Safety Research Review." FHWA-RD-99-092, McLean, Va., Federal Highway Administration, (1999))

(Carnahan, C. R., Fox, W. C., French, K. A., Hange, W. A., Henderson, J. L., Hook, D. J. P., Imansepahi, A., Khattak, S. S., Paulson, J. D., Resseguie, J. K., Richey, J. M., and Searls, T. D., "Permissive Double Left Turns: Are They Safe?" Washington, D.C., ITE 1995 Compendium of Technical Papers, (1995) pp. 214-218.)
(Kulmala, R., "Safety at Rural Three- and Four-Arm Junctions: Development and Application of Accident Prediction Models." 233, Espoo, Finland, VTT Technical Research Centre of Finland, (1995))

4.2.6. Traffic Calming

Intersections are places where accidents tend to cluster. This section presents current knowledge regarding the effects on highway safety of traffic calming in intersections. Traffic calming in intersections includes all measures that are designed to reduce speed in the intersection, or reduce the number of conflicts between the various traffic movements passing through an intersection.

This section will present evidence on the safety effects of the traffic calming devices at intersections. Some of the evidence presented here is also presented in other sections of the Highway Safety Manual, in particular in Chapter 3's traffic calming section for roadway segments, and Section 4.3. The following measures have been included in this section:

- Road narrowing (curb extensions, bulbouts, curb bulbs)
- Raised intersections
- Raised pedestrian crosswalks
- Raised bicycle crossings

Converting intersections to roundabouts may be considered as a traffic calming measure; for the HSM, discussion of this treatment is provided in Section 4.1.1.

The main source of evaluation studies is the "Handbook of Road Safety Measures" (*5*). The studies referred to in that book have been updated by more recent studies that are easily available. An extensive literature search has not been performed.

Exhibit 4-74: Resources examined to investigate the safety effect of traffic calming at intersections

DOCUMENT	DESCRIPTION	COMMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	No AMFs. Not added to synthesis.
(Johansson, C., Garder, P., and Leden, L., "The Effect of Change in Code on Safety and Mobility for Children and Elderly as Pedestrians at Marked Crosswalks - A Case Study Comparing Sweden to Finland." Washington, D.C., 83rd Transportation Research Board Annual Meeting, (2004))	A case study comparing the results of a study from Sweden with a study from Finland	Not relevant for this section. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Accidents Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	No AMFs. Not added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "A Guide for Addressing Unsignalized Intersection Accidents." NCHRP Report 500 Volume 5, Washington, D.C., Transportation Research Board, National Research Council, (2003))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	No AMFs. Not added to synthesis.
(*59*) (Elvik, R., "Area-wide Urban Traffic Calming Schemes: A Meta-Analysis of Safety Effects." Accident Analysis and Prevention, Vol. 33, No. 3, Oxford, N.Y., Pergamon Press, (2001) pp. 327-336.)	A meta-analysis of 33 studies that evaluated the effect of traffic calming on safety	Suggested by NCHRP 17-18(4). Added to synthesis.
(Huang, H. F. and Cynecki, M. J., "The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior." FHWA-RD-00-104, McLean, Va., Federal Highway Administration, (2001))	Evaluated numerous traffic calming measures using before and after studies in 3 cities, and cross-sectional studies in 5 cities; employed surrogates (e.g., speeds and compliance)	Suggested by NCHRP 17-18(4). Not reviewed. Duplicates report FHWA-RD-99-135
(Ewing, R., "Impacts of Traffic Calming." Transportation Quarterly, Vol. 55, No. 1, Washington, D.C, Eno Foundation for Transportation Inc., (2000) pp. 33-46.)	Summarizes the results of hundreds of before-and-after studies of traffic calming	Suggested by NCHRP 17-18(4). Not reviewed. Duplicates report FHWA-RD-99-135
(King, M. R., "Calming New York City Intersections." Dallas, Tex., Urban Street Symposium Conference Proceedings, (2000))	Evaluated the effect of neckdowns on crashes at six locations in New York City; focused on pedestrian crashes	Suggested by NCHRP 17-18(4). Limited data presented in paper. Not added to synthesis.
(Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))	A report from a series of pedestrian safety synthesis reports, with the majority of the data from the United Kingdom	No AMFs. Not added to synthesis.
(Ekman, L. and Hyden, C., "Pedestrian Safety in Sweden." FHWA-RD-99-091, McLean, Va., Federal Highway Administration, (1999))	A report from a series of pedestrian safety synthesis reports, with the majority of the data from Sweden	No AMFs. Not added to synthesis.
Ewing, R. H., "Traffic Calming: State of the Practice." FHWA-RD-99-135, Washington, D.C., Federal Highway Administration, (1999))	Research of traffic calming measures and their inherent impacts on the immediate environment as well as the study of legal, emergency, and public effects	No AMFs. Not added to synthesis.
(Hummel, T., "Dutch Pedestrian Safety Research Review." FHWA-RD-99-092, McLean, Va., Federal Highway Administration, (1999))	A report from a series of pedestrian safety synthesis reports, with the majority of the data from the Netherlands	No AMFs. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Garder, P., Leden, L., and Pulkkinen, U., "Measuring the Safety Effect of Raised Bicycle Crossings Using a New Research Methodology." Transportation Research Record 1636, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 64-70.)	Before and after study of raised urban bicycle crossings in Sweden	Suggested by NCHRP 17-18(4). Added to Section 4.3 for bicyclist design.
(ITE Traffic Engineering Council, "Design and Safety of Pedestrian Facilities: A Recommended Practice of the Institute of Transportation Engineers." ITE Journal, Vol. RP-026A, Washington, D.C., Institute of Transportation Engineers, (1998))	A research report on the recommended design and safety of pedestrian facilities	No AMFs. Not added to synthesis.
(Mertner, J. and Jorgensen, L., "Effects of Traffic Calming Schemes in Denmark." Transactions on the Built Environment, Vol. 33, Southampton, United Kingdom, WIT Press, (1998) pp. 213-223.)	Before and after study of traffic calming in Denmark, evaluated safety	Suggested by NCHRP 17-18(4). Uses speed as measurement. Not added to synthesis.
(Catalano, V. V. and Schoen, J. M., "Neighborhood Traffic Management in Tuscon, Arizona." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 21-27.)	Report based on a 5-year history of actual program evidence from technical studies and neighborhood input	No AMFs. Not added to synthesis.
(Zein, S. R., Geddes, E., Hemsing, S., and Johnson, M., "Safety Benefits of Traffic Calming." Transportation Research Record 1578, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 3-10.)	Research based on individual traffic calming studies; 85 case studies were reviewed fro Europe, North America, and Australia	Reviewed by Elvik 2001. Too few data to be included in meta-analysis. Not added to synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	A review incorporating a variety of studies including accident data, facility design guidelines, route designation criteria, and evaluations of facilities based on observational analysis accident data	No AMFs. Not added to synthesis.

Exhibit 4-75 lists studies that have evaluated the effects of the measures included in this section. This analysis is based on (*59*) and has been updated by Elvik for NCHRP Project 17-27.

Exhibit 4-75: Studies that have evaluated effects on road safety of traffic calming at intersections

Study	Country	Design	Number of estimates
Road narrowing (curb extensions, bulbouts, curb bulbs)			
Engel and Thomsen 1983	Denmark	Simple before-after	1
Blakstad 1993	Norway	Simple before-after	1
Raised intersections			
Schnüll et al 1992	Germany	Simple before-after	4
Raised pedestrian crosswalks			
Engel and Thomsen 1983	Denmark	Simple before-after	2
Jones and Farmer 1988	Great Britain	Simple before-after	4

Raised pedestrian crosswalks			
Downing et al 1993	Pakistan	Before-after with comparison group	2
Blakstad 1993	Norway	Simple before-after	2
Raised bicycle crossings			
Gårder et al 1998	Sweden	Empirical Bayes before-after	1

Only two studies have been found that have evaluated the effects on accidents of widening sidewalks at intersections. The studies do not state if the intersections studied had three or four legs. Both are simple before-after studies not controlling for any confounding factors and therefore both of these studies have been rated as low quality. Accordingly, the standard error has been adjusted by a factor of 3.

Only one study has been found that evaluates safety effects of raised intersections. It is a simple before-after study, not controlling for any confounding factors. It has been rated as a low quality study. The standard error has been adjusted by a factor of 3.

Four studies have been identified that evaluate raised pedestrian crosswalks. Again, the quality of these studies leaves much to be desired. Three of these studies have been rated as low quality, one (Downing et al., 1993) medium-low quality. Standard errors have been adjusted by a factor of 3 in the three low quality studies and by a factor of 2.2 in the medium-low quality study.

One study has evaluated raised bicycle crossings. It employs state-of-the-art Empirical Bayes methodology and has been rated as a high quality study. The standard error has been adjusted by a factor of 1.2.

Exhibit 4-76 summarises the findings of the studies listed in Exhibit 4-75. Uncertainty in summary estimates of effect is stated as the standard error of the summary estimate.

There are very few estimates of the effects of widening sidewalks, constructing raised intersections or constructing raised bicycle crossings. All the summary estimates are close to zero and all are highly uncertain. Current evidence is therefore inconclusive as far as the effects of these measures are concerned.

Raised pedestrian crosswalks appear to reduce accidents. The effects may be overstated, as none of the studies have controlled for regression-to-the-mean or long-term trends in accident frequency.

Exhibit 4-76: Effects on accidents of various traffic calming treatments at intersections

Studies summarised (No. of Estimates)	Treatment/ Element	Setting	Intersection type & volume	Accident Type & Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
All studies (2 estimates)	Widen sidewalks at intersections	Not reported	Not reported	All types, Injury	1.116	1.260
All studies (2 estimates)	Raised intersections	Not reported	Four legs, type of traffic control unknown	All types, Injury	1.053	0.712
All studies (2 estimates)	Raised intersections	Not reported	Four legs, type of traffic control	All types, PDO	1.134	1.401

Studies summarised (No. of Estimates)	Treatment/ Element	Setting	Intersection type & volume	Accident Type & Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
			unknown			
All studies (10 estimates)	Raised pedestrian crosswalks	Not reported	Not reported	All types, injury	0.642	0.543
All studies (5 estimates)	Raised pedestrian crosswalks	Not reported	Not reported	Pedestrian, injury	0.545	0.937
All studies (5 estimates)	Raised pedestrian crosswalks	Not reported	Not reported	Vehicle, all severities	0.697	0.667
All studies (1 estimate)	Raised bicycle crossings	Not reported	Not reported	Bicycle accidents, injury	1.088	0.527

4.2.7. On-street Parking [Future Edition]

In future editions of the HSM, this section may discuss the safety impact of on-street parking near intersections. The impact of various distances from the intersection to parked cars may be of interest. This section will relate to the discussion of on-street parking on roadway segments in Chapter 3. Potential resources are listed in Exhibit 4-77.

Exhibit 4-77: Potential resources on the relationship between on-street parking at intersections and safety

DOCUMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
Bureau of Transport Economics, "The Black Spot Program 1996-2002: An evaluation of the First Three Years", www.dotars.gov.au/transprog/downloads/road_bs_matrix.pdf
(Humphreys, J. B., Box, P. C., Sullivan, T. D., and Wheeler, D. J., "Safety Aspects of Curb Parking- Executive Summary." FHWA-RD-79-75, Washington, D.C., Federal Highway Administration, (1978))

4.2.8. Intelligent Transportation Systems and Traffic Management

The following sections provide discussion on various Intelligent Transportation System (ITS) treatments at intersections and roundabouts. Automated intersection enforcement and red-light running is discussed.

Signal coordination, red-light hold systems, queue detection systems, and automated speed enforcement may be discussed in future editions of the HSM.

4.2.8.1. Signal Coordination [Future Edition]

Signal progression or signal coordination is generally used to increase capacity of a corridor. In a future edition of the HSM, this section will discuss the safety impacts of providing signal coordination. Potential resources are listed in Exhibit 4-78.

Exhibit 4-78: Potential resources on the relationship between signal coordination of adjacent intersections and safety.

DOCUMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))
Rakha, H., Medina, A., Sin, F., Dion, M., Van Aerde, M. and Jenq, J. (2000), "Traffic signal coordination across jurisdictional boundaries: field evaluation of efficiency, energy, environmental, and safety impacts", *Transportation Research Record* 1727.

4.2.8.2. Queue Detection System [Future Edition]

Queue detection systems are generally used to increase the operational level of service of an intersection. In future editions of the HSM, this section may discuss the safety impact of implementing queue detection systems. Various types of queue detection systems may be included in the discussion. Potential resources are listed in Exhibit 4-79.

Exhibit 4-79: Potential resources on the relationship between queue detection systems and safety.

DOCUMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))

4.2.8.3. Automated Intersection Enforcement and Red-Light Running

In an effort to mitigate accidents due to red-light running at signalized intersections, many jurisdictions have installed red-light cameras. These cameras are positioned along the approaches to intersections with traffic signals and can detect and record the occurrence of a red-light violation. Often, signing, public information programs and rotation of camera equipment will result in "spillover" effects at nearby intersections or throughout a jurisdiction.

This section contains information on the safety effect of red-light-camera systems at signalized intersections. FHWA's evaluation of the crash-related effects of RLC systems, including "spillover" effects to nearby untreated intersections will be addressed.

Exhibit 4-80: Resources examined on the relationship between automated enforcement and safety

DOCUMENT	DESCRIPTION	COMMENT
(*137*) (Shin, K. and Washington, S., "The Impact of Red Light Cameras on Safety in Arizona", *Accident Analysis and Prevention*, 39, (2007), pp. 1212-1221)	Used several approaches (including EB) to study the safety impact of red light cameras in Scottsdale and Phoenix, Arizona. EB approach was possible only in Scottsdale. The study did	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
	not examine spillover effects at non-RLC equipped intersections were not examined. In addition, it is not clear if trend effects were considered in the EB evaluation in Scottsdale.	
(*138*) (Sayed, T. and de Leur, P., "Evaluation of Intersection Safety Camera Program in Edmonton, Canada", *Transportation Research Record* 2009, (2007), pp. 37-45)	Used the EB before-after approach to study the safety effect of mobile red light cameras at 25 intersections in Edmonton, Canada. The study did not examine spillover effects at non RLC locations.	Added to synthesis
(*139*) (Miller, J.S., Khandelwal, R., and Garber, N.J., "Safety Impacts of Photo-Red Enforcement at Suburban Signalized Intersections: An Empirical Bayes Approach", Transportation Research Record 1969, (2006), pp. 27-34) (Garber, N. J., Miller, J. S., Eslambolchi, S., Khandelwal, R., Mattingly, M., Sprinkle, K. M., and Wachendorf, P. L., "An Evaluation of Red Light Camera (Photo-Red) Enforcement Programs in Virginia: A Report in Response to a Request by Virginia's Secretary of Transportation." VTRC 05-R21, Charlottesville, Va., Virginia Transportation Research Council, (2005))	A before-after study using the EB approach was conducted to evaluate the impact of red light cameras at 13 signalized intersections in Fairfax County, Virginia. The study does not indicate if spillover effects at non-camera sites and other confounding factors were accounted for in the evaluation.	Added to synthesis.
(*62*) (Persaud, B., Council, F. M., Lyon, C., Eccles, K., and Griffith, M., "A Multi-Jurisdictional Safety Evaluation of Red Light Cameras.", *Transportation Research Record* 1922, (2005) pp. 29-37.)	A highly relevant resource combining data from 7 different jurisdictions in the U.S. EB approach including consideration of RTM results in recent and statistically defensible AMFs for consideration in this subsection	Added to synthesis.
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Red light cameras are not explicitly considered in the report.	Not added to synthesis.
(*63*) (Council, F. M., Persaud, B., Lyon, C., Eccles, K., Griffith, M. S., Zaloshnja, E., and Miller, T., "Economic Analysis of the Safety Effects of Red Light Camera Programs and the Identification Factors Associated with the Greatest Benefits." Washington, D.C., Presented at 84th Transportation Research Board Annual Meeting, (2004) pp. 1-11.)	This report builds on the results of reference 3280. It presents an economic analysis to further define the safety benefits of red-light cameras and is therefore referenced in this subsection.	Added to synthesis.
(Garder, P., "Traffic Signal Safety: Analysis of Red-Light Running in Maine." Orono, Maine Department of Transportation, (2004))	Report considers crash statistics involving red-light running in the State of Maine. No specific evaluation was done of red-light cameras.	Not added to synthesis.
(Bonneson, J. A. and Son, H. J., "Prediction of Expected Red-Light-Running Frequency at Urban Intersections." Transportation Research Record, No. 1830, Washington, D.C., Transportation Research Board, National Research Council, (2003) pp. 38-47.)	The study considers factors that affect the frequency of red-light running including approach flow rate, cycle length, yellow change interval, speeds, etc. No AMF's for red light cameras were considered.	Not added to synthesis.
(McGee, H. W. and Eccles, K. A., "Impact of Red Light Camera Enforcement on Crash Experience." *NCHRP Synthesis of Highway Practice*, No. 310, Washington, D.C., Transportation Research Board, (2003))	Examines what impact red light camera enforcement has had on crashes and related crash severity at intersections. Insufficient empirical evidence to state effect conclusively.	Not added to synthesis.
(Council, F. M. and Persaud, B., "Red Light Camera Safety Evaluation - Experimental Design, Draft Final Report. Appendix A." (2002))	Proposed evaluation design for national study of crash effects of RLC systems. Includes critical reviews of past RLC studies but no new	Suggested by NCHRP 17-18(4). Not

DOCUMENT	DESCRIPTION	COMMENT
	data to supplement the findings of this subsection.	added to synthesis.
(Retting, R. A., Chapline, J. F., and Williams, A. F., "Changes in Crash Risk Following Re-timing of Traffic Signal Change Intervals." Accident Analysis and Prevention, Vol. 34, No. 2, Oxford, N.Y., Pergamon Press, (2002) pp. 215-220.)	Report considers the affects of changing the change intervals for traffic signals. No specific AMF's or crash information was provided for red light cameras.	Not added to synthesis.
(Maccubbin, R. P., Staples, B. L., and Salwin, A. E., "Automated Enforcement of Traffic Signals: A Literature Review." Washington, D.C., Federal Highway Administration, (2001))	Report provides a summary of other research. No new information was provided.	Not added to synthesis.
(Retting, R. A. and Kyrychenko, S. Y., "Crash Reductions Associated with Red Light Camera Enforcement in Oxnard, California." Arlington, Va., Insurance Institute for Highway Safety, (2001))	Reports crash reduction in three cities, unable to identify crashes related to red-light running events. Superseded by Persaud et al study.	Not added to synthesis.
(Smith, D. M., McFaden, J., and Passetti, K. A., "Automated Enforcement of Red Light Running Technology and Programs: A Review." Transportation Research Record, No. 1734, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 29-37.)	Evaluated the effect of automated enforcement systems on crashes and violations at intersections in three cities in the U.S., conducted in NY, FL, and MD. The report considers the stages of the implementation programs and does not provide sufficient information to develop AMF's.	Suggested by NCHRP 17-18(4). Not added to synthesis.
(Datta, T. K., Schattler, K., and Datta, S., "Red Light Violations and Crashes at Urban Intersections." Washington, D.C., 79th Transportation Research Board Annual Meeting, (2000))	Paper considers the effects of all-red intervals, exclusive left turn lanes and left-turn phases on accidents. No red-light camera evaluations were considered.	Not added to synthesis.
(Mohamedshah, Y., Chen, L., and F.M.Council, "Association of Selected Intersection Factors With Red-Light-Running Crashes." FHWA-RD-00-112, McLean, Va., Federal Highway Administration, (2000))	Study considers the characteristics of intersections that are susceptible to red light running accidents. No specific AMF's or crash information was provided for red light cameras.	Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	Some discussion of speed control is mentioned, however, there is no explicit discussion of the effectiveness of red-light cameras on safety.	Not added to synthesis.
(McFadden, J. and McGee, H. W., "Synthesis and Evaluation of Red Light Running Automated Enforcement Programs in the United States." FHWA-IF-00-004, Washington, D.C., Federal Highway Administration, (1999))	Evaluated the effect of automated enforcement systems on crashes and violations at intersections in five cities in the U.S. A repeat of reference 3081.	Suggested by NCHRP 17-18(4). Not added to synthesis.

Treatment: Install red-light cameras at intersections

Since red-light camera technologies emerged over 30 years ago, applications have been assessed throughout the world in terms of the effects on safety. The most defensible and comprehensive study was completed by Persaud, Council, Lyon, Eccles, and Griffith (2005) (*62*). The results from this study are provided in Exhibit 4-77 and recommended for the HSM. This study considers data acquired from red-light camera installations in 13 jurisdictions throughout the United States. However, through a selective review of the data against the requirement of high priority data elements (e.g. crash, ADT, signal phasing changes, RLC signage) the study narrowed the data sample to 7 jurisdictions and explicitly considered the data at 132 treatment sites with 408 and 296 reference and comparison groups (*62*).

The study employed an Empirical Bayesian methodology and accounted for RTM. No further adjustments to the index of effectiveness were required, and a method correction factor of 1.2 was used to reflect a regression comparison where all potential confounding factors considered during a review of the study are accounted for. Persaud et al. found that, with the introduction of red-light cameras, a decrease in the right angle accidents is expected (25% for all severities and 16% for injury accidents) with a corresponding increase in rear-end accidents (15% for all severities and 24% for injury accidents) (Exhibit 4-81) (*62*). These findings are consistent with the findings of previous studies on the topic and suggest that red-light cameras may be best suited for locations that have a high number of angle accidents and a correspondingly lower number of rear-end accidents. A companion paper from Council et al. (2005) provides a closer examination of this assumption using economic analysis (*63*).

Shin and Washington, used several approaches (including EB) to evaluate the safety of red light cameras in Phoenix and Scottsdale, Arizona (*137*). The evaluation included 10 intersections in Phoenix and 14 intersections in Scottsdale. The EB method was not applied in evaluating the Phoenix installations because a complete reference group was not available for that city. In addition, it is not clear if (and how) the trend effects were accounted for the in the EB evaluation of the Scottsdale intersections. The authors also acknowledge that the study did not specifically account for spillover effects at non-RLC intersections. The EB evaluation of the Scottsdale sites revealed a 17% reduction in angle crashes, 40% reduction in left turn crashes, and a 45% increase in rear-end crashes. The results of the EB analysis are shown in the Exhibit. The EB analysis was rated Medium High and an MCF of 1.8 was used to adjust the standard errors from this study. The results from Persaud et al. were combined with Shin and Washington and recommended for inclusion in the HSM.

Miller et al. used several approaches (including EB) to evaluate the safety of 13 intersections with red light cameras in Fairfax, Virginia (*139*). The study paper/report does not indicate whether spillover effects to non-RLC intersections were accounted for. The results indicate a 33% reduction in red light running crashes, 34% reduction in injury red light running crashes, 59% increase in rear end crashes, 14% increase in total injury crashes, and 12% increase in total crashes. The increase in rear end crashes is much higher than the increase found in other EB studies. The authors argue that one reason for this increase is that in the Miller et al. study, only those rear-end crashes attributable to the presence of the red phase were defined as rear-end crashes unlike most other studies that included all rear-end crashes.

Unlike the three other studies discussed here, Sayed and de Luer evaluated the safety of a mobile red light camera enforcement system in Edmonton using the before-after EB method (*138*). Up to 60 locations are included with a total of 24 enforcement cameras available for deployment. Twenty five sites were selected for evaluation – all of them were four leg intersections with a speed limit of 50 km/h. All crash types including angle, rear end, and total crashes decreased following the implementation of the cameras. Angle crashes decreased between 17 and 20% and rear-end crashes decreased between 12 and 14%. The authors acknowledge that the study did not specifically account for spillover effects at non-RLC intersections.

Exhibit 4-81: Safety effectiveness of red light cameras on accidents

Author, date	**Treatment / Element**	**Setting**	**Intersection type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Persaud et al., 2005	Red Light Cameras	California, Maryland, North Carolina	Entering AADTs: Minor road: 12562 to 33679, Major road: 52625 to 109067	Right Angle and left turn, All Severities	0.75	0.035
Persaud et al., 2005	Red Light Cameras	California, Maryland, North Carolina	Entering AADTs: Minor road: 12562 to 33679, Major road: 52625 to 109067	Right Angle and left turn, Injuries	0.84	0.071
Persaud et al., 2005	Red Light Cameras	California, Maryland, North Carolina	Entering AADTs: Minor road: 12562 to 33679, Major road: 52625 to 109067	Rear End, All Severities	1.15	0.036
Persaud et al., 2005	Red Light Cameras	California, Maryland, North Carolina	Entering AADTs: Minor road: 12562 to 33679, Major road: 52625 to 109067	Rear End, Injuries	1.24	0.139
Shin and Washington, 2007	Red Light Cameras	Scottsdale, Arizona		Right angle and left-turn, all severities	0.665	0.076
Shin and Washington, 2007	Red Light Cameras	Scottsdale, Arizona		Rear-end, all severities	1.45	0.108
Combined Persaud et al., 2005 and Shin and Washington, 2007	Red Light Cameras	California, Maryland, North Carolina, and Arizona		Right angle and left-turn all severities	**0.735**	**0.032**
				Rear-end, all severities	**1.180**	**0.034**
				Right angle and left-turn, injuries	**0.84**	**0.071**
				Rear-end, Injuries	**1.24**	**0.139**

4.2.8.4. Automated Speed Enforcement [Future Edition]

In future editions of the HSM, this section may discuss the safety effects of photo radar enforcement at the approaches to the intersection. Drone radar may also be discussed in this section. Potential resources are listed in Exhibit 4-82.

Exhibit 4-82: Potential resources on the relationship between automated enforcement and safety

DOCUMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
Retting and Farmer, "Evaluation Of Speed Camera Enforcement In The District Of Columbia" TRR 1830 "Highway Safety, Traffic Law Enforcement, and Truck Safety", 2003

4.3. Pedestrian and Bicyclist Safety at Intersections

Pedestrians and bicyclists are more vulnerable road users, and consideration of their needs at intersections, particularly in urban areas, may impact the overall safety performance of an intersection. Several sources are available for information on pedestrian and bicyclist accommodation including pedestrians with disabilities, such as:

- www.walkinginfo.org
- www.bicycleinfo.org
- AASHTO "Guide for the Planning, Design and Operations of Pedestrian Facilities", 2004 (*26*)
- "ADA and ABA Accessibility Guidelines for Buildings and Facilities", 2004 (*65*)
- "NCHRP Report 500 Volume 10: A Guide for Reducing Crashes Involving Pedestrians" by Zegeer et al., 2004 (*66*)
- "Pedestrian Facilities Users Guide – Providing Safety and Mobility" by Zegeer et al., 2002 (*25*)
- Parts I and II of "Designing Sidewalks and Trails for Access" by Axelson, Kirschbaum, et al., 1999 and 2001 (*67,68*)
- "Design and Safety of Pedestrian Facilities: A Recommended Practice of the ITE", 1998 (*69*)
- "The Effects of Bicycle Accommodations on Bicycle/Motor Vehicle Safety and Traffic Operations" by Wilkinson et al., 1994 (*70*)

The design of accessible pedestrian facilities is required and is governed by implementing regulations under the Rehabilitation Act of 1973 and the Americans with Disabilities Act (ADA) of 1990, which reference specific design and construction standards for usability(*71*).

One of the most comprehensive guides describing a wide range of treatments to enhance pedestrian safety and mobility is the PEDSAFE Guide, sponsored by the Federal Highway Administration (*72*). This report provides details of 47 different types of engineering and roadway treatments, in addition to enforcement and educational measures. It also includes a description of 71 "case studies" (or success stories) of various pedestrian treatments which have been implemented in communities throughout the U.S.

The PEDSAFE Guide includes expert system software, which is available at http://safety.fhwa.dot.gov/pedsafe and also at www.walkinginfo.org/pedsafe. This software is a diagnostic tool which allows a user to select treatments based on the types of crash or operating problems at a site, as well as site characteristics (e.g., number of lanes, type of roadway, traffic volume, area type, traffic control devices, intersection or midblock, presence and type of median, speed limit). The system provides information to help identify safety and operational needs. The PEDSAFE Guide and software are intended primarily for engineers, planners, safety officials, but may also be useful to citizens in determining needed pedestrian improvements on streets and highways.

The following sections discussed pedestrian and bicyclist elements at intersections, such as pedestrian crossing design, median refuge islands, bicycle operations, and pedestrian and bicyclist traffic control. Future editions of the HSM may include sections on pedestrians and bicyclists at roundabouts, and the impact of weather issues on pedestrians and bicyclists at intersections.

4.3.1. Pedestrian Crossing Design

This section provides information on the safety effects of various design elements for pedestrian crossings at signalized and unsignalized intersections, excluding roundabouts.

Additional information on addressing the needs of all pedestrians through design can be found in Parts I and II of "Designing Sidewalks and Trails for Access" (*67*,*68*).

The following discussion includes several topics related to intersection design treatments that may affect pedestrians, including:

- Road narrowing (curb extensions, bulbouts, curb bulbs, lane narrowing, visual enclosure, curb radius)
- Raised crosswalks
- Raised intersections
- Bus stop location
- Pedestrian crossing speed

Related sections of the HSM include Sections 4.2.2 Traffic Signal Operations, 4.2.6 Traffic Calming, 4.3.4 Pedestrians and Bicyclists at Roundabouts [Future Edition], and 4.4.3 Signal Heads and Hardware.

Exhibit 4-83: Resources examined on the relationship between pedestrian crossing design and safety at intersections

DOCUMENT	DESCRIPTION	COMMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Crashes at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Summaries strategies to reduce crashes at signalized intersections, with minimal information on pedestrian treatments at intersections	No new information. Not added to synthesis.
(*41*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians, including the safety effects of treatments at intersections	Added to synthesis.
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results may be added if relevant when available.

DOCUMENT	DESCRIPTION	COMMENT
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Crashes Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Includes information and research summaries on strategies to reduce pedestrian crashes, including geometric pedestrian treatments at intersections	Added to Section 4.3.2.
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook that summarizes the effects of a wide range of safety measures.	Added to synthesis
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Synthesis of past research on a variety of treatments, but does not include intersection design treatments for pedestrians	Not added to synthesis.
(Lord, D., "Synthesis on the Safety of Right Turn on Red in the United States and Canada." Washington, D.C., 82nd Transportation Research Board Annual Meeting, (2003))	Study involved collecting observational data at 26 intersections in the province of Quebec and also analyzed pedestrian crash data involving RTOR from agencies in the U.S. and Canada	Added to Section 4.2 and 4.3.5.
Raford, Noah; and Ragland, R. David. Space Syntax: An Innovative Pedestrian Volume Modeling Tool for Pedestrian Safety. Institute of Transportation Studies, U.C. Berkeley Traffic Center, 2003.	This study focuses on estimating pedestrian exposure by using a method called Space Syntax. The purpose of this report is to help planners and engineer to have estimates of pedestrian exposure data since such information is rather scarce.	No treatments were considered and hence no safety effect was estimated. Not added to synthesis
(*75*) (Huang,H.F. , Cynecki,M.J., “The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior” FHWA-RD-00-104, McLean, Va., Federal Highway Administration (2000))	Evaluated curb extensions at a total of eight locations in Cambridge, Seattle, Greensboro (NC), and Richmond (VA), based on pedestrian wait time, vehicle speed, and motorist yielding behavior	Added to synthesis.
(*73*) (Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))	Summarizes findings from the U.K on pedestrian safety research, including “curb build-outs” (curb extensions)	Added to synthesis.
(Hummel, T., "Dutch Pedestrian Safety Research Review." FHWA-RD-99-092, McLean, Va., Federal Highway Administration, (1999))	Summarizes pedestrian safety research in the Netherlands. Minimal information is given on specific effects of geometric treatments at intersections.	Not added to synthesis.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	An article which provides a discussion of pedestrian designs and treatments. No information is given on geometric design measures at intersections	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Kulmala, R., "Safety at Rural Three- and Four-Arm Junctions: Development and Application of Accident Prediction Models." 233, Espoo, Finland, VTT Technical Research Centre of Finland, (1995))	Before-After study of the safety effectiveness of several geometric design elements at rural three- and four-leg intersections	Not added to synthesis. More relevant to intersection design.
(Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	Report to Congress.	Added to Section 4.3.5.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Provides a summary of a critical review of literature on the safety effects of roadway geometric features on pedestrian and bicycle safety. No information is included on intersection geometric measures related to pedestrians	Not added to synthesis.
(Zegeer, C. V. and Cynecki, M. J., "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." Transportation Research Record 1059, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 24-34.)	Collected observational data on more than 67,000 drivers at 110 intersections in Washington, D.C., Dallas, Austin, Detroit, Lansing, and Grand Rapids. Studied motorist violations of NO TURN ON RED (NTOR) signs	Used in section for pedestrians and bicyclists and traffic control. Not added to synthesis.
(Lalani, N., "Road Safety at Pedestrian Refuges." Traffic Engineering & Control, Vol. 18, No. 9, London, United Kingdom, Hemming Information Services, (1977) pp. 429-431.)	Before and after study of the effect of pedestrian refuges on crashes; sites in London.	Added to Section 4.3.2.

Treatment: Implement road narrowing and curb extensions

Narrowing the roadway width using curb extensions (sometimes called chokers, curb bulbs, neckdowns, or nubs) extends the curb line or sidewalk out into the parking lane, and thus reduces the effective street width for crossing pedestrians. Such reduction in street width can reduce vehicle speeds, improve visibility between pedestrians and oncoming motorists, as well as reduce the crossing distance for pedestrians.

In his summary report of pedestrian research in the U.K., Davies reported in Nottingham (by Thompson and Heyden, 1991) where curb extensions were extended 2.5 meters into the street and included “substantial lengths of guardrail,” (assumed to be protective railing for pedestrians). The authors reported a reduction in average pedestrian crashes from 4.7 to 1 per year after the treatment (*73*). Insufficient information was available to determine an AMF from this study.

A 2001 study by Huang and Cynecki involved evaluating curb extensions at a total of eight locations in Cambridge, Seattle, Greensboro (NC), and Richmond (VA), based on pedestrian wait time, vehicle speed, and motorist yielding behavior. No significant improvements were found at most of the sample sites after curb extensions were installed. Huang and Cynecki stated that some of the results may have been due to traffic conditions at the study sites. The authors also stated that such devices cannot guarantee that motorists will slow down or yield to pedestrians, or that pedestrians will choose to cross at the crosswalk (*75*).

In their 2001 report, Huang and Cynecki report several other studies that have involved the evaluation of curb extensions, as follows (*75*):

- MacBeth evaluated five raised and narrowed intersections in Ontario, Canada, as well as seven mid-block pedestrian crossing locations, where the speed limit was also lowered to 30 km/h. The proportion of motorists exceeding the 30 km/h speed limit was reduced from 86% in the before period to 20% in the after period. Several treatments were applied in conjunction at these locations; therefore the safety effect of curb extensions alone cannot be determined.
- A study in the Netherlands (as cited by Replogle) involved street narrowing projects in two towns. In Oosterhout, two bulbouts were installed which required motorists to deviate from a straight roadway path, and the 85th percentile speeds and the rate of pedestrian/motor vehicle conflicts dropped after installation of the bulbouts. Two bulbouts were installed opposite each other to narrow the travel way in De Meern, which resulted in a significant reduction in the 85th percentile speed. However, the magnitude of the reduction was not reported by Huang and Cynecki.
- A 1992 study by Lumilla in Australia reported that bulbouts had little effect on vehicle speeds in the cities of Keilor (Queensland) and Eltham (Victoria). That same study, however, reported that a street treated with bulbouts and marked parking lanes had a total crash rate that was one third of the rate of an untreated comparison street. Huang and Cynecki did not indicate the number of crashes which involved pedestrians, or the type of parking lanes provided.

Based on recent meta-analysis work by Elvik and Vaa (2004) (*5*), only two studies have been found that have evaluated the effects on accidents of road narrowing, or widening sidewalks, at intersections, one from Denmark and the other from Norway. The studies do not state if the intersections studied had three or four legs. Both were simple before-after studies not controlling for any confounding factors and therefore both of these studies have been rated as low quality. Accordingly, the standard error has been adjusted by a factor of 3. The result of a meta-analysis of these two studies is provided in Exhibit 4-84.

Exhibit 4-84: Effects on accidents of road narrowing and curb extensions at intersections (5)

Author, date	**Treatment/ Element**	**Setting**	**Intersection type & volume**	**Accident Type & Severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa (2004)	Widen sidewalks at intersections	Not reported	Not reported	All types, Injury	1.116	1.260

Treatment: Install raised pedestrian crosswalks

Elvik and Vaa (2004) (*5*) recently performed a meta-analysis of four international studies that evaluated raised pedestrian crosswalks. Three of these studies have been rated as low quality, one (Downing et al., 1993) medium-low quality. Standard errors have been adjusted by a factor of 3 in the three low quality studies and by a factor of 2.2 in the medium-low quality study. Intersection types and volumes were not reported by Elvik and Vaa. The resulting indices of effectiveness are presented in Exhibit 4-85. Based on these values, raised pedestrian crosswalks appear to reduce accidents. The effects may be overstated, as none of the studies have controlled for regression-to-the-mean or long-term trends in accident frequency.

Exhibit 4-85: Effects on accidents of raised pedestrian crossings at intersections

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident Type & Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa (2004)	Raised pedestrian crosswalks	Not reported	Not reported	All types, injury	0.642	0.543
Elvik and Vaa (2004)	Raised pedestrian crosswalks	Not reported	Not reported	Pedestrian, injury	0.545	0.937
Elvik and Vaa (2004)	Raised pedestrian crosswalks	Not reported	Not reported	Vehicle, all severities	0.697	0.667

Treatment: Install raised intersections

Huang and Cynecki evaluated the installation of a raised intersection in Cambridge, MA in their 2001 study (*75*). There was a significant increase in the percentage of pedestrians who crossed in the crosswalk, from 11.5% to 38.3%. There was an increase in the percentage of motorists who yielded to pedestrians in the crosswalk, but this increase was not statistically significant (due to small sample sizes). No AMFs could be developed from this study.

Based on recent work by Elvik and Vaa (2004), only one study has been found that evaluates safety effects of raised intersections (*5*). It is a simple before-after study, not controlling for any confounding factors, conducted in Germany by Schull et al. (1992). It has been rated as a low quality study. The standard error has been adjusted by a factor of 3. The setting and type of traffic control used was not reported. The results of Elvik and Vaa's analysis are provided in Exhibit 4-86.

Exhibit 4-86: Effects on accidents of raised intersections

Author, date	Treatment/ Element	Setting	Intersection type & volume	Accident Type & Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa (2004)	Raised intersections	Not reported	Four legs, type of traffic control unknown	All types, Injury	1.053	0.712
Elvik and Vaa (2004)	Raised intersections	Not reported	Four legs, type of traffic control unknown	All types, PDO	1.134	1.401

Discussion: Bus stop location at intersections

Crashes at bus stops account for 2% of all pedestrian crashes in urban locations. These accidents usually occur when a pedestrian tries to cross the street in front of a stopped bus and is struck by a motorist whose vision was obstructed by the bus. In rural areas, 3% of all pedestrian accidents occur at school bus stops (*41*).

For the urban crashes, one solution is relocating a bus stop to the far side of an intersection so that pedestrians are more likely to cross the street behind the bus rather than in front of it. A before-after study by Berger in 1975 (as noted by Campbell et al.) of two intersections where bus stops were relocated in Miami, FL, and San Diego, CA, showed that the relocation to the far side of the intersection eliminated crossing in front of the bus; whereas, in the period before relocation, half the people who crossed the street after getting off the bus crossed in front of it (*41*). No AMFs could be developed for bus stop locations at intersections.

4.3.1.1. Crosswalk Markings

According to the 1992 Uniform Vehicle Code (Section 1-112) (*76*), a crosswalk is defined as:

That part of a roadway at an intersection included within the connections of the lateral lines of the sidewalk on the opposite sides of the highway measured from the curbs, or in the absence of curbs, from the edges of the traversable roadway; and in the absence of a sidewalk on one side of the roadway, the part of a roadway included within the extension of the lateral lines of the existing sidewalk at right angles to the centerline.

Any portion of a roadway at an intersection or elsewhere distinctly indicated for pedestrian crossing by lines or other markings on the surface.

Legal crosswalks, therefore, exist at all intersections on public streets and highways where there is a sidewalk on at least one side of the road and/or where crosswalk markings exist, while a legal crosswalk only exists at a midblock location if it is marked. According to the MUTCD (Section 3B-18) (*17*), a crosswalk may be marked with paint, plastic tape, thermoplastic materials, or other materials. The marking of crosswalks has been quite controversial in the U.S. in recent years at uncontrolled locations (i.e., locations where no traffic signals or stop signs exist on the approach at either intersection or midblock locations). Recent safety research on crosswalks, as discussed below, has helped to resolve some of the controversy on this issue.

Marked crosswalks are typically installed at signalized intersections, as well as school zones and some unsignalized intersections. Acceptable crosswalk marking patterns are given in the MUTCD (*17*). Crosswalks may be raised (sometimes termed “speed tables”) or used in conjunction with supplemental signing, in-pavement flashing lights, overhead flashers, nighttime lighting, pedestrian refuge islands, signalization, and/or other devices.

This chapter summarizes the safety effects of marked vs. unmarked crosswalks on pedestrian crashes and also provides some discussion on pedestrian and motorist behavior at intersections related to crosswalk markings. This section also includes a review of studies of advance stop lines and signing which supplement marked crosswalks at intersections. Finally, information is summarized on studies (from the United Kingdom) that have evaluated the effects of such crossing measures as Zebra, Pelican, Puffin, and Toucan pedestrian crossings. Details on the treatment of pedestrian crossings to adequately accommodate people with disabilities are contained in Parts I and II of “Designing Sidewalks and Trails for Access” (*67*,*68*), and will not be repeated in this manual.

Pedestrian signal options commonly used at intersections in the U.S. are discussed in the chapter on traffic control devices (Section 4.3.5).

Based on the information found in the literature on marked crosswalks, there is a considerable amount of useful information on the crash effects of marked vs. unmarked crosswalks (from the study by Zegeer et al., 2002) and of the effects of marked crosswalks on pedestrian and motorist behavior (e.g., Knoblauch et al., 2000). However, there is a particular need for further research to better quantify the effects of crosswalk enhancements on pedestrian crashes, as well as pedestrian and motorist behaviors. Such crosswalk enhancements include advance warning signs, crosswalk flashing lights, overhead illuminated pedestrian crossing signs, crosswalk marking types and patterns, and other measures. It would also be useful to have a formal evaluation of the effect of advance stop lines on pedestrian crashes on multi-lane roads. Finally, there is a need to develop more detailed criteria of the types of pedestrian crossing treatments that would be most appropriate for installation on streets having various combinations of number of lanes, traffic ADT, area type, speed limit, and other conditions.

Exhibit 4-87: Resources examined to investigate the safety effect crosswalk markings at intersections

DOCUMENT	DESCRIPTION	COMMENT
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Crashes at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Provides crash-related countermeasures at signalized intersections, with only a brief mention of crosswalks and enhancements	Not added to the synthesis
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Crashes Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Provides details of 16 strategies to reduce pedestrian crashes, including crosswalk enhancements	Added to Section 4.3.2.
(*41*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Contains a summary of relevant research studies	Used as a source of information for this chapter. Added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Summarizes crosswalk evaluation study by Knoblauch and Raymond (2002)	Provides no new information - Used as a reference only. Not added to the synthesis
(*77*) (Zegeer, C. V., Stewart, R., Huang, H., and Lagerwey, P., "Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines." FHWA-RD-01-075, McLean, Va., Federal Highway Administration, (2002))	Evaluated the safety effects of marked vs. unmarked crosswalks, based on 1,000 marked and 1,000 unmarked crossing sites at uncontrolled intersections in 30 cities.	Added to synthesis. Main source of information on the safety effects of marked crosswalks for various traffic and roadway conditions
(Zegeer, C. V., Stewart, J. R., Huang, H., and Lagerwey, P., "Safety Effects of Marked Versus Unmarked Crosswalks At Uncontrolled Intersections." Transportation Research Record, No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 56-68.)	Same study as (*77*).	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*79*) (Knoblauch, R. L., Nitzburg, M., and Seifert, R. F., "Pedestrian Crosswalk Case Studies: Richmond, Virginia; Buffalo, New York; Stillwater, Minnesota." FHWA-RD-00-103, McLean, Va., Federal Highway Administration, (2001))	Before and after study of crosswalk markings at 11 unsignalized intersections in 4 cities, evaluated indirect measures such as driver and pedestrian behavior	Suggested by NCHRP 17-18(4). Added to synthesis.
(Van Houten, R., Malenfant, J. E., and McCusker, D., "Advance Yield Markings: Reducing Motor Vehicle-Pedestrian Conflicts at Multilane Crosswalks with Uncontrolled Approach." Transportation Research Record, No. 1773, Washington, D.C., Transportation Research Board, National Research Council, (2001) pp. 69-74.)	Evaluated the effect of advance yield markings and a symbol sign on pedestrian safety at intersections; used pedestrian and motorist behavior as surrogate	Suggested by NCHRP 17-18(4). Added to synthesis as cited in (*73*)
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Summarizes various studies on pedestrian crossing treatments at uncontrolled approaches to intersections, signalized intersections, and mid-block signals	Suggested by NCHRP 17-18(4). Not added to synthesis. No additional information.
(*81*) (Knoblauch, R. L. and Raymond, P. D., "The Effect of Crosswalk Markings on Vehicle Speeds in Maryland, Virginia and Arizona." FHWA-RD-00-101, Great Falls, Va., Federal Highway Administration, (2000))	Study of crosswalks at six sites in Maryland, Virginia, and Arizona.	Added to the synthesis
(*82*) (Jones, T. L. and Tomcheck, P., "Pedestrian Accidents in Marked and Unmarked Crosswalks: A Quantitative Study." ITE Journal, Vol. 70, No. 9, Washington, D.C., Institute of Transportation Engineers, (2000) pp. 42-46.)	Evaluation of pedestrian crashes at "unprotected" crosswalks in Los Angeles.	Added to synthesis.
(Cairney, P., "Pedestrian Safety in Australia." FHWA-RD-99-093, McLean, Va., Federal Highway Administration, (1999))	The report states that: "The installation of crosswalks has not been contentious in Australia, and there is no research on their effectiveness".	Not added to the synthesis
(*83*) (Ekman, L. and Hyden, C., "Pedestrian Safety in Sweden." FHWA-RD-99-091, McLean, Va., Federal Highway Administration, (1999))	Summarizes the results from several crosswalk evaluation studies	Added to the synthesis
(*73*) (Davies, D. G., "Research, Development and Implementation of Pedestrian Safety Facilities in the United Kingdom." FHWA-RD-99-089, McLean, Va., Federal Highway Administration, (1999))	Discusses studies which evaluated the effects of zebra, pelican, and toucan crossings in the U.K.	Added to the synthesis
(*84*) (Van Houten, R. and Malenfant, J. E. L., "Canadian Research on Pedestrian Safety." FHWA-RD-99-090, McLean, Va., Federal Highway Administration, (1999))	Summarizes studies which evaluated crosswalk enhancements	Added to the synthesis
(Hunt, J., "A Review of the Comparative Safety of Uncontrolled and Signal Controlled Midblock Pedestrian Crossings in Great Britain." Cologne, Germany, 9th International Conference on Road Safety in Europe, (1998))	Review of performance of Pelican and Zebra crossings in Kent (U.K.).	No AMFs, conflicting results. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Mueller, E. A. and Rankin, W. W., "Pedestrians." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 8, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Contains a summary of pedestrian research studies conducted prior to 1970	Not added to the synthesis

Marking crosswalks at uncontrolled locations (i.e., no traffic signal or stop sign control, either midblock or on approach to intersection) is discussed first, including some findings on pedestrian crashes, motorist behavior, pedestrian behavior, and driver speed. This is followed by a discussion of the use of alternative marking patterns, such as the “zebra” or “ladder” marking. Information in this chapter primarily deals with intersections, although some studies include analysis of crosswalks at midblock locations as well as intersections.

Discussion: Mark crosswalks at uncontrolled locations (intersection and midblock)

In the most comprehensive study of marked crosswalks at uncontrolled intersection and midblock locations to date, Zegeer, Stewart, Huang, and Lagerwey (2002) analyzed data from 1,000 marked and 1,000 matching unmarked crosswalk sites in 30 U.S. cities (*77*). Zegeer et al. determined that some site factors (area type, speed limit, and crosswalk marking pattern) were not associated with pedestrian crashes. Site factors that were related to pedestrian crashes which were used as control variables in the analysis included pedestrian ADT, vehicle ADT, number of lanes, median type, and region of the United States. With these factors accounted for, Poisson and negative binomial regression models were used to determine the crash effects of marked vs. unmarked crosswalks.

At uncontrolled locations on two-lane roads and multi-lane roads with low traffic volumes (i.e., ADT below 12,000 veh/day), it was found that a marked crosswalk alone, compared with an unmarked crosswalk, made no statistically significant difference in pedestrian crash rate. On multi-lane roads with an ADT of more than 12,000 veh/day, a marked crosswalk by itself (without other substantial improvements) was associated with a statistically significant higher pedestrian crash rate compared to sites with an unmarked crosswalk.

On multi-lane roads, raised medians in marked or unmarked crosswalks provided statistically significant lower crash rates than no raised median.

The crash rates for older pedestrians were higher than for other pedestrian-age groups, considering pedestrian crashes and exposure by age. Furthermore, older pedestrians were more likely than younger pedestrians to cross at a marked crosswalk, which may partially explain the higher pedestrian crash rate at marked crosswalks. Another reason for higher pedestrian crashes at marked crosswalks were multiple threat crashes that occurred on multi-lane roads (i.e., a vehicle in the curb lane stops for a pedestrian in the crosswalk and the pedestrian crossing into the second lane and into the path of an oncoming vehicle that may not be aware of the pedestrian).

Zegeer et al. state that, “The results of this study should not be misused as justification to do nothing to help pedestrians to safely cross streets. Instead, pedestrian crossing problems and needs should be routinely identified, and appropriate solutions should be selected to improve pedestrian safety and access. Deciding where to mark or not mark crosswalks is only one consideration in meeting that objective” (*77*), page 1). Zegeer et al. suggested a number of potential improvements at unsignalized crossing locations to enhance pedestrian safety. Some of these recommendations include: providing raised medians on multi-lane roads, installing traffic and pedestrian signals where warranted, adding curb extensions or raised islands to reduce street-crossing distance, installing adequate nighttime lighting at pedestrian crossings, constructing raised street crossings, designing safer intersection and driveways (e.g., with tighter turn radii), among others (*77*).

In conjunction with the Zegeer et al.'s research on crosswalks done for FHWA, Knoblauch performed two studies on pedestrian and motorist behavior. One of these studies was an effort to assess the effect of crosswalk markings on driver and pedestrian behavior at 11 unsignalized locations in four U.S. cities (*79*). All of the sites were two- or three-lane roads with relatively low speed limits (35 to 40 mph) and low volumes (less than 12,000 veh/day). Given these characteristics, the authors concluded that marking pedestrian crosswalks had no measurable negative effect on either pedestrian or motorist behavior. Crosswalk usage increased after markings were installed, but no evidence was found that pedestrians were less vigilant or more assertive in the marked crosswalk. Drivers were found to approach a pedestrian in the crosswalk rather slowly, but no changes in driver yielding were noted. Details on the duration of the study periods were not reported.

Knoblauch's second study was performed at six sites in Maryland, Virginia, and Arizona (*81*). All of these locations were uncontrolled intersection approaches (i.e., no traffic signals or stop control for the study approach) with a 35 mph speed limit and had been recently resurfaced. Using a staged pedestrian at sample crossing locations, speed data were taken under three conditions: no pedestrian present, pedestrian looking, pedestrian not looking. Results indicated a slight reduction in vehicle approach speeds at most, but not all, of the locations after the crosswalk markings had been installed. There was a significant reduction in overall speed under conditions of no pedestrians and where pedestrians were not looking.

Several studies prior to the studies by Zegeer et al. (2002) and Knoblauch et al. (2000) produced a wide range of results concerning the safety effects of marked vs. unmarked crosswalks. Most of these older studies discussed below, were conducted between 1972 and 1994, and concluded that pedestrian crashes were higher in marked crosswalks, compared to unmarked crosswalks. However, note that none of these earlier studies attempted to analyze the effects of marked vs. unmarked crosswalks specifically for different numbers of lanes, traffic volume, or other roadway features.

Jones and Tomcheck (2000) evaluated pedestrian crashes at "unprotected" crosswalks (i.e., at unsignalized intersections) on arterials in Los Angeles to test the validity of the city's crosswalk policies (*82*). The study attempted to determine whether removing a crosswalk marking reduces pedestrian crashes at such locations, and/or increase pedestrian crashes at adjacent unprotected sites. Jones and Tomcheck analyzed pedestrian crashes at 104 unsignalized intersections on arterials where marked (parallel-line) crosswalks had been removed due to resurfacing. Jones and Tomcheck state that the locations were not chosen for the pedestrian accident histories. The study did not include school crosswalks. At many intersections, some legs had both marked and unmarked crosswalks before and after the study. An average of approximately 7 years of pedestrian crash data was collected for each of the before and after periods for the 104 sites. Traffic and pedestrian exposure data were not collected, but untreated comparison sites were identified and used in the analysis.

When only the legs of the intersections that previously had marked crosswalks are considered, Jones and Tomcheck found that there was a 73% reduction (from 116 to 31) in pedestrian crashes after crosswalk markings were removed at the 104 sites combined (*82*). Considering both legs (previously marked and unmarked crosswalks) of the intersections, there was a statistically significant decline of 61% (from 129 to 50) in pedestrian crashes (*82*). There was no statistically significant increase in pedestrian crashes at intersections adjacent to intersections where crosswalk markings were removed. At the 15 intersections where crosswalk markings were retained (i.e., untreated "comparison sites"), pedestrian crashes did not decrease. The authors recommended supporting… "a policy of selectively installing or reinstalling marked, unprotected crosswalks only after careful consideration" (*82*). It should be noted that the study did not report the effects of removing crosswalk markings by road type (i.e., two-lane vs. multi-lane) or volumes at the study sites. Also, the study mentions that "when a street is to be resurfaced, a plan is prepared to update the roadway striping … unprotected marked crosswalks are analyzed to see whether they should be retained" (pg 43) (*82*). Jones and Tomcheck do not clearly state if the crosswalks that were removed were deemed to be unnecessary, or the criteria used to make that determination. This may influence the results of the Jones and Tomcheck study.

In the often-cited 1972 San Diego study by Herms, crashes on marked crosswalks were found to be twice as frequent per unit of pedestrian volume, compared to unmarked crosswalks (Herms, 1972 as cited in (*41*)). Herms looked at 400 intersections in the city, each of which had one marked and one unmarked crosswalk leg on the same street. In an earlier version of the same study (Herms, 1970), the author mentioned San Diego's 1962 warrants for determining where to paint crosswalks. The city's warrants required marking crosswalks when traffic gaps were inadequate, pedestrian volume was high, speed was moderate, and/or there were other relevant factors such as previous crashes. These criteria suggest that crosswalks in San Diego were painted where the conditions were already most conducive to pedestrian crashes or which already had a history of pedestrian crashes.

As documented by Campbell et al. (*41*), authors of the Zegeer et al. study (2002) attempted to compare their results with those of the 1972 Herms San Diego study. Taking all of the 2,000 sites together as one group and simply dividing the crashes by pedestrian crossing volume (as Herms did), the Zegeer group also found that marked crosswalks had a pedestrian crash rate that was slightly more than twice the rate of unmarked crosswalk sites. Only when a more sophisticated statistical analysis was applied did the researchers find that marked crosswalks are associated with higher pedestrian crash risk only on high-volume, multi-lane roads (i.e., ADT above 12,000 veh/day).

In 1994, Gibby et al. analyzed crashes at 380 unsignalized highway intersections in California from among 10,000 candidate intersections throughout the state (Gibby et al., 1994 as cited in (*41*)). Crash rates per pedestrian-vehicle volume were two or three times higher in marked than in unmarked crosswalks at these sites. As with the Herms study, this study combined all sites with marked crosswalks and unmarked crosswalks, and did not conduct a separate analysis for different cross-sections, traffic volumes, etc.

A 1985 Toronto study (Yagar) found that crashes had been increasing and continued to increase at the same rate after marked crosswalks were installed at 13 intersections within the city (as cited by (*41*)). This suggests that marking the crosswalks had little effect. However, there were more tailgating crashes after the crosswalks were painted. Yagar also explained the increasing crashes after installation of the marked crosswalks as a problem with out-of-town motorists.

Tobey et al. (1983) examined crashes at both marked and unmarked crosswalks as a function of pedestrian volume (P) multiplied by vehicle volume (V) and, unlike some of the previous studies cited here, reported fewer accidents at marked crosswalks than at unmarked ones (Tobey et al., 1983 as cited in (*41*)). However, this may be due to the fact that Tobey's study included signalized as well as uncontrolled crossings and it is likely that more marked crosswalks were at controlled locations than unmarked crosswalks were. It should be mentioned that the study methodology was designed to determine the pedestrian crash rate for a variety of human and location conditions, but was not specifically intended to quantify the isolated safety effects of marked vs. unmarked crosswalks.

In 1974, Gurnett described a project in which painted crosswalk stripes were removed from three locations because of a recent bad crash history (Gurnett, 1974 as cited in (*41*)). There were fewer crashes after removal of the stripes, but these findings might simply be due to regression-to-mean, since the only sites that were "treated" (i.e., crosswalks were removed) were those that had a recent history of pedestrian crashes.

In 1967, the Los Angeles County Road Department found that accident frequency increased from four to 15 after marked crosswalks were installed at 89 non-signalized intersections (as cited in (*41*)). All the locations that showed an increase in crashes after crosswalk installation had an ADT of greater than 10,900 vehicles; sites with fewer vehicles experienced no change in pedestrian crashes. This is consistent with the findings of the Zegeer study mentioned earlier.

As documented by Campbell et al. (*41*), a study in London (Mackie and Older, 1965) calculated crash risk as the ratio of crashes per unit time to pedestrian volume counts. The authors discovered a gradient effect, with risk lower in marked crosswalks (zebra pattern) than in the areas up to 50 yards (45.7 m) away. Crash risk increased nearer to the marked crossing, although within the crossing the crash risk was lower (*41*). In contrast, Campbell et al. cite Swedish researchers (Ekman, 1988) who found that pedestrians are exposed to a double risk of injury when using a marked (zebra) crosswalk than crossing at a location without any signs or road markings (*41*).

Despite the contradictory findings of these various studies, it is clear that marked crosswalks are generally not associated with any statistically significant difference in pedestrian crash risk (compared to unmarked crosswalk sites) on two-lane roads or on multi-lane roads with less than 12,000 veh/day. On multi-lane roads with ADT higher than 12,000 veh/day, marked crosswalks installed alone without other substantial safety devices carry significantly increased crash risk for pedestrians, unless more substantial pedestrian safety treatments are provided (*41*). The safety professional may consider such crossing treatments (e.g., raised medians on multi-lane roads, traffic and pedestrian signals, where warranted, adequate nighttime lighting at pedestrian crossings, etc.) to help pedestrians to cross streets more safely.

Discussion: Advance stop lines and other crosswalk enhancements at marked crosswalks at intersections

In an effort to determine factors that would influence motorists to yield for pedestrians in marked crosswalks, Van Houten (1992) applied a sequential series of enhancements at intersections in Dartmouth, Nova Scotia (as cited in (*73*)). First, signs were added; then a stop line; and finally amber lights activated by the pedestrians. The number of vehicles that stopped when they should increased by up to 50%; conflicts dropped from 50% to 10% at one location and from 50% to 25% at another site. Motorists who yielded to pedestrians went up from 25% to 40% at one site and from 35% to 45% elsewhere.

Using sites in Newfoundland and New Brunswick, Canada, researchers (Malefant and Van Houten, 1989 as cited in (*73*)) looked for ways to increase the number of drivers who yield to pedestrians. Additional roadway markings, feedback to pedestrians regarding compliance, warning signs for drivers, and enforcement were all used to encourage yielding behavior. The response to these multiple interventions was successful, with increased percentages of motorists who yielded to pedestrians ranging from 50% before the interventions to 70% afterwards in one city; 10% to 60% in another locale; and 40% to 60% in the third one.

In 1993, Cynecki, Sparks, and Grote studied the effects of transverse rumble strips installed in advance of marked crosswalks at 19 uncontrolled locations (as cited in (*73*)). There was little change in vehicle speed; 85^{th} percentile speeds showed no real change.

Discussion: Behavioral studies of marked vs. unmarked crosswalks

Due to the wide range of findings on the effects of marked vs. unmarked crosswalks from the crash-based research, it is also important to closely examine studies of pedestrian and motorist behavior at marked vs. unmarked crosswalks, particularly since some of the authors cited above offered "opinions" on such behaviors to support their findings. For example, in his 1972 study conclusions, Herms stated, "Evidence indicates that the poor crash record of marked crosswalks is not due to the crosswalk being marked as much as it is a reflection on the pedestrian's attitude and lack of caution when using the marked crosswalk". Other authors agreed with this assessment about the pedestrian's attitude and behavior in a marked crosswalk (e.g., *Public Works*, 1969; Los Angeles County Road Department, 1967). The following is a summary of some of these studies which involved evaluating pedestrian behavior on marked vs. unmarked crosswalks.

Pedestrian Behavior

Knoblauch et al. (2001) launched a study intended to observe the type of reckless pedestrian behavior to which Herms and others attributed the negative crash results reported in some of the marked crosswalk studies (as cited in (*41*)). The researchers gathered data at eleven sites before and after marked crosswalks were installed, evaluating the information in terms of three hypotheses regarding pedestrian behavior. The findings for each hypothesis were:

- Hypothesis 1 – Will pedestrians feel more protected in a marked as opposed to an unmarked crosswalk and therefore act more aggressively? The research team found no statistically significant difference in blatantly aggressive behavior.
- Hypothesis 2 – Will pedestrians stay within the marked lines of the crosswalk? Pedestrians walking alone did tend to use the marked crosswalks, especially at intersections, while pedestrian groups did not. Overall crosswalk usage did increase statistically significantly after markings were added.
- Hypothesis 3 – Because they feel more protected, will pedestrians engage in less "looking behavior" when crosswalks are marked? Looking behavior actually increased after markings were installed; no evidence of decreased vigilance was found.

For the most part, these findings were consistent with an earlier study of pedestrian behavior done by Knoblauch et al. (1987) that considered the effect of marked crosswalks on pedestrian looking behavior and staying within the area defined by the markings (*41*). The duration of the observations were not reported.

Hauck (1979) evaluated 17 crosswalks at traffic signals that were re-painted in Peoria, IL (as cited in (*41*)). A before- after analysis found a decrease in both pedestrian and motorist violations at the sites after installation of marked crosswalks. Jaywalking was unchanged, but the number of people who stepped out in front of traffic decreased at 12 of the locations and those crossing against the DON'T WALK signal phase decreased at 13 sites.

The studies suggest that pedestrian behavior is generally improved by marking crosswalks. There is no indication of reckless behavior associated with marked crosswalks.

Motorist Behavior

Knoblauch (2000) took speed measurements at six locations before and after marked crosswalks were installed (as cited in (*41*)). Speeds were measured: 1) with no pedestrians present; 2) with a member of the research team posing as a pedestrian who was looking at traffic; and 3) when the team member approached and stood at the curb looking straight across the road rather than at oncoming traffic. Motorist behavior was not consistent, so the results were not clear-cut. At one site, drivers slowed down considerably even when no pedestrians were present. When a pedestrian was present and looking at traffic, there was a small but not statistically significant decrease in speed at all six locations. Knoblauch reasoned that drivers might assume a pedestrian looking toward oncoming traffic would not try to cross the street, so vehicles did not need to slow down. However, when the pedestrian was present and not looking for oncoming cars, drivers approaching the marked crosswalk did slow down enough to register a statistically significant change. Knoblauch's conclusion was that drivers usually respond to crosswalk markings, especially when a pedestrian is present but not watching traffic (*41*).

In 2001, Knoblauch et al. studied motorist behavior on two- and three-lane roads with 35 to 40 mph speed limits and found the following answers to these two questions (as cited in (*41*)):

1. Do crosswalk markings affect the motorist's response to pedestrians? Drivers did seem to slow down a little more as they approached pedestrians in marked crosswalks as opposed to unmarked crossings.
2. Would marked crosswalks disrupt the flow of traffic by causing drivers to stop and yield to pedestrians? There was no observable change and no real difference between the yielding behavior with regard to pedestrians in a marked vs. unmarked crosswalk.

Ekman (1988) found that Swedish drivers did not slow down when approaching zebra crossings, which is understandable in that speeds were measured when no pedestrians were present in the crosswalk or at the curb (as cited in (*41*)).

Campbell et al. (*41*) cite another Swedish study (Varhelyi, 1996) that measured speeds at non-signalized zebra crossings. Motorists maintained or even increased their speeds in 73% of what the author labeled "critical" cases and only slowed down 27% of the time when they should have. Despite this reality, a separate survey showed that 67% of the motorists responding said they "always" or "very often" slow down (*41*).

Katz et al. (1975) studied driver-pedestrian interaction when members of the research team crossed the street under a variety of conditions in 960 trials. Drivers were more likely to stop for pedestrians when the vehicle approach speed was low, when the pedestrian was in a marked crosswalk, when the distance between the car and pedestrian was greater rather than less, when there was a group of pedestrians, and when the pedestrians did not make eye contact with the driver (as cited in (*41*)).

In summary, the presence of marked crosswalks seems to have little, if any, consistent effect on motorist speed or behavior. However, it appears that drivers at lower speeds are more likely to stop and yield to pedestrians than higher-speed motorists.

Summary

Despite the contradictory findings of these various studies, it is clear that marked crosswalks are generally not associated with any difference in pedestrian crash risk (compared to unmarked crosswalk sites) on two-lane roads or on multi-lane roads with less than 12,000 veh/day. On multi-lane roads with ADT higher than 12,000 veh/day, marked crosswalks installed alone without other substantial safety devices carry statistically significant increased crash risk for pedestrians, unless more substantial pedestrian safety treatments are provided. Based on studies of pedestrian and motorist behavior, pedestrian behavior is generally improved by marking crosswalks, and no indication of reckless behavior has been found associated with marked crosswalks. However, most of these behavioral studies were on two- or three-lane roads, where no differences were found in pedestrian crash risk between marked and unmarked crosswalks. On many roads (particularly for multi-lane roads with ADT above about 12,000 veh/day), the safety professional may consider such crossing enhancements as raised medians on multi-lane roads, advanced stop lines, traffic and pedestrian signals (where warranted), adequate nighttime lighting at pedestrian crossings, etc., to help pedestrians to cross streets more safely.

4.3.2. Median Refuge Islands

Pedestrian crossings at intersections are sometimes designed with a median refuge island; otherwise referred to as center islands, refuge islands, pedestrian islands, or median slow points. Median refuge islands are raised areas that help protect pedestrians who are crossing the road, either at an intersection or mid-block. The presence of a median refuge island in the middle of a street or intersection allows pedestrians to focus on just one direction of traffic at a time and then take refuge on the island while waiting for an adequate gap in cars coming from the other direction before continuing to walk across the road. Islands are appropriate for use at both uncontrolled (i.e., no traffic signals or stop signs) and signalized crosswalk locations. Where the road is wide enough and on-street parking exists, center islands can be combined with curb extensions to enhance pedestrian safety (*66*).

According to the new AASHTO Pedestrian Guide (*26*), medians and crossing islands should be at least 6 ft (1.8 m) wide, which allows room for more than one pedestrian to wait, as well as 2 ft (0.6 m) wide detectable warnings for the visually impaired on either side of the island. A median width of 8 ft (2.4 m) is recommended “where practical” to accommodate wheelchairs, bicycles, scooters, and groups of pedestrians. The recommended length of an island (parallel to the street) is 20 ft (6.1 m), large enough to protect potential users of the island by making it visible to approaching motorists. The AASHTO Pedestrian Guide also recommends that islands have a level landing area of at least 4 ft (1.2 m) square, to provide a resting area for wheelchairs. Criteria for maximum slope of ramps and detectable warnings are set forth in the Guide and also in ADA Accessibility Guidelines (*65*).

This section will compare the safety of pedestrian crossings at intersections with median refuge islands as opposed to those without refuge islands. The section will include crash-based studies, as well as research using pedestrian and/or motorist behavior as a measure of safety effectiveness. This section will also include some information with regard to different design elements and marking, signing, and other devices that are sometimes used to supplement median refuge islands.

Based on the available research on the topic of median refuge islands at intersections, there are clear needs for future research. First, there is a need to conduct a large-scale evaluation on the crash effects of refuge islands under a wide range of traffic and roadway conditions (e.g., for two-lane vs. multi-lane roads, varying traffic and pedestrian conditions, area types, signalized vs. unsignalized crossings, and varying speed conditions). This could be evaluated using a properly designed before-after study (with control sites) or a comparative analysis. A crash-based study must account for pedestrian volume conditions, since adding a refuge island will undoubtedly attract some pedestrians to cross where the refuge island was installed (and thus cause an increase in pedestrian crossing activity at the refuge island and a decrease at nearby sites without refuge islands).

There is also a need to determine the effects of design features (e.g., curb extensions, width of refuge island) and traffic control devices (signing, crosswalk markings, advance warning devices), which may be used to supplement intersection refuge islands. Based on the available literature, there is a need to develop general guidelines or recommendations on when and where the installation of intersection refuge islands is most appropriate and beneficial.

Exhibit 4-88: Resources examined to investigate the safety effect of median refuge islands at intersections

DOCUMENT	**DESCRIPTION**	**COMMENT**
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Crashes at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	No information on ped refuge islands	Not added to the synthesis.
(Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Contains a summary of relevant research studies	Used as reference. Not added to synthesis.
(*66*) (Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Crashes Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Includes a discussion of refuge islands and a summary of some research studies involving refuge islands	Added to the introduction.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Summarizes research results from several studies on refuge islands	Not added to the synthesis.
(*77*) (Zegeer, C. V., Stewart, R., Huang, H., and Lagerwey, P., "Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines." FHWA-RD-01-075, McLean, Va., Federal Highway Administration, (2002))	Matched comparison of 5 years of crash data at 1,000 marked crosswalks and 1,000 unmarked crosswalks	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Bacquie, R., Egan, D., and Ing, L., "Pedestrian Refuge Island Safety Audit." Monterey, Calif., Presented at 2001 ITE Spring Conference and Exhibit, (2001))	Study of midblock pedestrian crossings.	Not added to the synthesis.
(*75*) (Huang, H. F. and Cynecki, M. J., "The Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior." FHWA-RD-00-104, McLean, Va., Federal Highway Administration, (2001))	Before and after evaluation of pedestrian and motorist behaviors at 4 sites	Added to the synthesis.
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Summarizes research and practice related to uncontrolled crossings	Not added to the synthesis.
(Garvey, P. M., Gates, M. T., and Pietrucha, M. T., "Engineering Improvements to Aid Older Drivers and Pedestrians." Traffic Congestion and Traffic Safety in the 21st Century Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 222-228.)	Refuge islands are only mentioned briefly	Not added to the synthesis.
(Staplin, L., Harkey, D. L., Lococo, K. H., and Tarawneh, M. S., "Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians Volume: I: Final Report." FHWA-RD-96-132, McLean, Va., Federal Highway Administration, (1997))	Refuge islands are only mentioned briefly	Not added to the synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	General discussion of refuge islands	Not added to the synthesis.
(*89*) Garder,P., "Pedestrian Safety at Traffic Signals" Accident Analysis and Prevention Vol.21, Oxford, N.Y. (1989)	Analyzed intersections in two Swedish cities (Stockholm and Malmo)	Added to the synthesis.
(*88*) Garder,P., Hyden,C., Linderholm,L., "Samband mellan olycksrisk och olika forklaringsvariabler" LTH Bulletin 27, Lund, Sweden (1978)	Studied effects of refuge islands on serious conflicts with pedestrians	Added to the synthesis.
(*87*) (Lalani, N., "Road Safety at Pedestrian Refuges." Traffic Engineering & Control, Vol. 18, No. 9, London, United Kingdom, Hemming Information Services, (1977) pp. 429-431.)	Before and after study of the effect of pedestrian refuges on crashes; sites in London.	Suggested by NCHRP 17-18(4). Added to the synthesis.

Discussion: Install median refuge islands at marked or unmarked crosswalks at signalized or unsignalized intersections

Zegeer et al. studied 2,000 crossing sites in 30 cities; all sites were in urban or suburban areas and included primarily arterial and collector streets (*77*). Streets covered a range of speed limits, typically 25 to 40 mph. Sites were selected within a variety of area types (i.e., residential, downtown, commercial, urban fringe, etc.). Zegeer et al. found that the presence of a raised median or refuge island was associated with a statistically significantly lower rate of pedestrian crashes on multi-lane roads (compared to no median or refuge island). This was true at marked as well as unmarked crosswalks. All sample sites used in the study were uncontrolled crossings at intersection (i.e., no traffic signals or STOP-control on intersection approach of interest) or mid-block locations. The presence of painted (not raised) medians or islands and two-way-left-turn lanes provided no statistically significant reduction in pedestrian crash rate on multi-lane roads. The study collected and controlled for pedestrian and vehicle exposure, along with other site variables in the analysis (*77*).

The purpose of a study by Lalani in 1977 was to compare personal injury crashes before and after installation of "Double-D" shaped refuge islands at 120 sites, including intersection and mid-block, marked and unmarked locations in London, England. These islands were installed in conjunction with other roadway improvements, such as anti-skid surfacing, illuminated bollards, bus lanes, and crosshatch markings. Although the use of central refuge islands is generally considered to enhance pedestrian safety, this study found that refuges reduced vehicle crash frequency but increased pedestrian accident frequency at intersections (*87*).

Lalani also determined that (*87*):

- At intersections, vehicular accident frequency was significantly reduced only when the refuge islands were reinforced with hatch markings to channelize motor traffic;
- At midblock locations, vehicular accidents were only reduced where the islands had internally illuminated bollards; and
- Pedestrian accidents were only reduced at sites where the refuge islands were constructed on roads next to high pedestrian generators. (It is unclear if Lalani is referring to intersection or midblock or both.)

It is possible that the results of the Lalani study (i.e., the increase in pedestrian crashes after installation of refuge islands) may be a manifestation of the fact that more pedestrians are drawn to use the crossing after a refuge island is installed. A study of all of the pedestrian crashes along a road section (with corresponding pedestrian exposure) and controlling for pedestrian exposure at the crossings would allow for quantifying this effect.

A 1978 study in Sweden by Garder was conducted to determine the effects of refuge islands on serious conflicts with pedestrians (*88*). Based on studies at 115 intersections (termed "junctions") in Sweden from 1974 to 1976, serious pedestrian conflicts were reduced by approximately 20% on low-speed (less than 19 mph, or 30 km/h) intersections after the installation of "central traffic islands". On higher-speed intersections, serious pedestrian conflicts were about 60% lower after installation of the islands. The risk of pedestrian conflicts at signalized (two-phase) intersections was reduced by about 30% after central traffic islands were installed. However, the results were not statistically significant (*88*). Pedestrian volumes and other characteristics of the locations studied were not reported.

In 1989, Garder analyzed intersections in two Swedish cities (Stockholm and Malmo), concluding that the installation of a median refuge island decreased pedestrian crash risk by one third (*89*). The measurement of pedestrian crash risk is not clear from the literature. However, the percentage of pedestrians who crossed on a red light (i.e., "red-walking") was higher when a refuge island was present than not (15% as opposed to 10%) (*89*). The configuration and traffic control at the study intersections were not reported.

A study by Huang and Cynecki (2001) involved before-after analysis of a variety of traffic calming measures in several U.S. cities, using pedestrian and motorist behavior as measures of effectiveness. The study included an evaluation of four refuge islands at two unsignalized four-leg intersections in Sacramento, California, across streets that were two-way, two-lane with parking on both sides and zebra crosswalks at the refuge islands. The refuge islands constricted the width of the travel lanes and were expected to reduce vehicle speeds, increase the number of pedestrians for whom motorists yielded, and increase the percentage of pedestrians who crossed in the crosswalk (*75*).

After installation of pedestrian refuge islands at the four crosswalk locations, the percentage of motorists who yielded to pedestrians increased from 32.6% to 42.1% (*75*). This was not statistically significant (at the 90% level), due to relatively small sample sizes of crossing pedestrians. However, there was a statistically significant increase in the percentage of pedestrians who crossed in the crosswalk (from 61.5% to 71.9%) (*75*). There was no statistically significant difference in the pedestrian wait time after the refuge islands were installed. It would be expected that pedestrian wait time would more likely be improved in situations where refuge islands are installed on multi-lane roads.

There is strong evidence from crash-based studies and also from behavioral studies that raised median refuge islands provide a significant safety benefit for pedestrians at intersections. The benefits of islands are most likely pronounced on multi-lane roads, where pedestrians only have to cross half of the street at a time and can then wait on the refuge island for gaps in motor vehicle traffic before crossing the second half of the street. Median refuge islands must be properly designed and visible to motorists to prevent crashes involving vehicles striking the island.

4.3.3. Bicyclist Design Considerations

The safety of bicyclists at intersections depends on many factors related to geometric and traffic control conditions. Guidelines for the planning, design, and operation of bicycle facilities are provided in the 1999 “Guide for the Development of Bicycle Facilities” report by AASHTO (*90*). Specific design information is given in that document related to treatments for bicyclists at intersections, including sight distance, signs, signals and markings, proper design of bike lanes at intersections, transition zones, approach treatments, refuge islands, and others.

According to Hunter et al. (1996), 50% to 70% of all crashes between bicycles and motor vehicles occur at or near intersections. A number of countermeasures have been developed and tested in the U.S. and abroad to facilitate the safe passage of bicyclists through intersections. Much of the information below related to bicycles was adopted from a summary of literature compiled by Hunter et al. for “A Comparative Analysis of Bicycle Lanes versus Wide Curb Lanes: Final Report” (*91*).

This section provides information on roadway design features to accommodate bicyclists at signalized and unsignalized intersections. Specific treatments discussed include:

- Bike lanes at intersections
- Grade separation
- Offset or discontinuous bike lanes at intersections
- Raised, painted bicycle crossings

Section 3.3 provides discussion of bicycle treatments along roadway segments.

There is a need to conduct further research to better quantify the effects of bike lanes and wide curb lanes on bicycle crashes and conflicts for a variety of traffic and roadway conditions. Also, more testing is needed to better quantify the effect on behaviors, conflicts, and crashes of such treatments as raised bike lane crossings.

Exhibit 4-89: Resources examined to investigate the safety of bicyclists at intersections

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results may be added if relevant when available.
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook that summarizes the effects of a wide range of safety measures.	Added to synthesis
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Brief summary of past research on a variety of treatments	No new information. Not added to synthesis
(Jensen, S. U., "Cyclist Safety at Signalised Junctions." Amsterdam, Netherlands, Velo Mondial 2000, (2000))	Danish study that evaluated the effect of advance bicycle merging treatments on bicyclist crashes at 11 intersections in Denmark	Suggested by NCHRP 17-18(4). Not added to synthesis – more relevant to bicycle traffic control.
(Hunter, W. W., "Evaluation of a Combined Bicycle Lane/Right Turn Lane in Eugene, Oregon." FHWA-RD-00-151, McLean, Va., Federal Highway Administration, (2000))	Compared conflicts at an intersection with a combined bicycle lane/right-turn lane to a similar intersection with a standard right lane and bike lane to the left in Eugene, Oregon	Suggested by NCHRP 17-18(4). Not added to synthesis
(*91*) (Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. F., and Pein, W. E., "A Comparative Analysis of Bicycle Lanes versus Wide Curb Lanes: Final Report." *FHWA-RD-99-034*, McLean, Va., Federal Highway Administration, (1999))	Comparative analysis of bicycle lanes versus wide curb lanes, sites in CA, FL, and TX, used conflicts as surrogate for safety	Suggested by NCHRP 17-18(4). Added to synthesis
(Hunter, W. W., Stewart, J. R., and Stutts, J. C., "A Study of Bicycle Lanes Versus Wide Curb Lanes." Transportation Research Record: Journal of the Transportation Research Board, No. 1667, Washington, D.C., Transportation Research Board, (1999) pp. 70-77.)	Comparative analysis of bicycle lanes versus wide curb lanes, sites in CA, FL, and TX, used conflicts as surrogate for safety	Not added to synthesis. Same information as above reference (final report of same study)
(Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. H., and Pein, W. E., "Bicycle Lanes Versus Wide Curb Lanes: Operational and Safety Findings and Countermeasure Recommendations." FHWA-RD-99-035, McLean, Va., Federal Highway Administration, (1999))	Comparative analysis of videotaped behavior of bicyclists and motorists at 16 intersections with either a bike lane or wide curb lane; sites in CA, FL, and TX; also looked at conflicts and lateral positioning of bicyclists	Not dded to synthesis. No information not provided in final report of same study.
(*93*) (Hunter, W. W., Harkey, D. L., and Stewart, J. R., "Portland's Blue Bike Lanes: Improving Safety through Enhanced Visibility." Portland, Ore., City of Portland, (1999))	Study of colored bike lanes in Portland, Oregon.	Limited qualitative information added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Brude, U. and Larsson, J., "The Safety of Cyclists at Roundabouts: A Comparison between Swedish, Danish, and Dutch Results." Nordic Road and Transport Research, No. 1, Linköping, Sweden, Johnny Dahlgren Grafisk Produktion AB, (1997) pp. 23-25.)	A summary of safety studies on cyclist safety at roundabouts from Sweden, Denmark, and the Netherlands	This article to be covered under Pedestrian and Bicyclist Safety at Roundabouts. Not added to synthesis.
(*94*) (Jensen, S. U., "Junctions and Cyclists." Barcelona, Spain, Proc. Velo City '97 - 10th International Bicycle Planning Conference, (1997))	Evaluation of raised crossings for bicycles, some of which were marked with blue pavement, at signalized intersections in Denmark	Limited information added to synthesis. No AMFs.
(*61*) (Garder, P., Leden, L., and Pulkkinen, U., "Measuring the Safety Effect of Raised Bicycle Crossings Using a New Research Methodology." *Transportation Research Record 1636*, Washington, D.C., Transportation Research Board, National Research Council, (1998) pp. 64-70.)	Before and after study of raised urban bicycle crossings in Sweden	Suggested by NCHRP 17-18(4). Added to synthesis.
(Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	Report to Congress	No AMFs. Not added to synthesis.
(Wilkinson, W. C., Clarke, A., Epperson, B., and Knoblauch, R., "The Effects of Bicycle Accommodations on Bicycle/Motor Vehicle Safety and Traffic Operations." FHWA-RD-92-069, Washington, D.C., Federal Highway Administration, (1994))	Conclusions are provided on bicycle planning and design based on the current state of the practice; recommendations are based on a literature review	Used as a reference. Not added to synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Summarizes the safety effectiveness of various geometric features on pedestrian and bicycle safety, based on critical reviews of literature	Used as a reference. Not added to synthesis.
(Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M., "The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents." Journal of Safety Research, Vol. 13, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 45-55.)	Examined the effects of RTOR on pedestrian safety	Not relevant to this section. Not added to synthesis.

Discussion: Provide bicycle lanes at intersections

A bicycle lane (BL) is defined as a part of the roadway designated for bicycle traffic and separated from motor vehicles in adjacent lanes by pavement markings. Most often, bicycle lanes are installed near the right edge of the road, although they are sometimes placed to the left of right-turn lanes or on-street parking. Bike lanes at intersections have been evaluated in several studies.

A Danish study (Jensen, 1997) looked at the effect of BLs on accident rates at signalized intersections and at priority intersections (at priority intersections, traffic is controlled by signage rather than signals and one road has priority over the other). Results indicated that the implementation of BLs caused no change in the number of either bicycle-motor vehicle or overall crashes at signalized intersections. However, there was an increase in bicycle-motor vehicle crashes at priority intersections. The study also found a reduction in all crashes along the stretches of roadway between intersections (*94*). No further details regarding the study were reported.

A comparative analysis of bicycle lanes (BLs) versus wide curb lanes (WCLs) was conducted for the FHWA in 1999 (*91*). In the cities of Santa Barbara, CA, Gainesville, FL, and Austin, TX, videotapes were made of bicyclists approaching and riding through eight intersections that had BLs and eight others that had WCLs. At the BL locations, 2,700 cyclists were observed, while 1,900 cyclists were taped going through the WCL intersections. In addition, brief on-site interviews of 2,900 bicyclists were conducted; and an analysis was performed on crash data from bicycle-motor vehicle crashes (*91*).

Hunter et al. showed that 5.6% of all bicyclists on the videotapes were riding the wrong way, against traffic, with significantly more of this behavior exhibited at WCL sites (1.7%) than at BL locations (1.0%). One-third of the bicyclists at both types of facilities claimed to be experienced riders (*91*).

The Hunter et al. study also showed that more people riding bicycles approached the intersection on a sidewalk at locations that had a WCL (15%) than where a BL (3%) was present. The type of bicycle facility available (WCL or BL) had no apparent effect on whether or not cyclists obeyed traffic signals. In fact, 92% of the videotaped bicyclists at the study sites complied with the signals. Seventy-five percent of the cyclists obeyed stop signs, but a higher percentage did so at BL locations (81%) than WCL sites (55%) (*91*).

A statistically significant difference was noted by Hunter et al. in the percentage of bicyclists who shied a little to the right, away from motor vehicle traffic, as they progressed straight through BL intersections (11%) compared with WCL locations (7%) (i.e., cyclists move further away from cars when they have a delineated bike lane). For cyclists turning left at the intersection, among those who did so motor vehicle-style (i.e., from the left-turn lane), 14% at the WCL locations turned improperly as opposed to 3% at the BL sites. More pedestrian-style left turns (i.e., dismounting and walking bike in crosswalks) were seen at WCL sites (24%) than at BL intersections (12%). (It should be noted that the WCL sites usually involved higher traffic volumes, speeds, and numbers of lanes). When bicyclists made right turns, a statistically significant 19% were done in a pedestrian-style at WCL locations compared to 10% at BL sites (*91*). It is not clear at this time which maneuver for conducting left-turns is safer.

In terms of conflicts occurring at the actual intersection, 198 were recorded on tape. Of these, 79% were bicycle/motor vehicle conflicts, 10% bicycle/bicycle conflicts, and 10% bicycle/pedestrian conflicts. Again, more bicycle/bicycle conflicts occurred in the BLs than in WCLs, with a greater proportion of bicycle/pedestrian problems in the WCLs. Over 90% of all midblock and intersection conflicts noted in this study were considered minor (*91*).

In their comment section, Hunter et al. suggest the findings contradict prevailing assumptions about the differences between WCLs and BLs. Many experts think that more experienced riders tend to use the WCLs and less proficient cyclists opt for BLs; survey results in this study found no difference in cyclist experience according to type of facility. Similarly, the common belief that riding the wrong way is more common among BL users was called to question by results of this study, which found a higher proportion of people going against traffic at the WCL sites. Of course, this might be due to the fact that WCLs are often found on higher volume roadways, where cyclists seek what they think is the safest route possible. Data from both

BL and WCL locations suggest the need for educating cyclists about the safest way to make both left and right turns at intersections (*91*).

Hunter et al. state that (*91*):

"The overall conclusion of this research is that both BL and WCL facilities can and should be used to improve riding conditions for bicyclists, and this should be viewed as a positive finding for the bicycling community. The identified differences in operations and conflicts were related to the specific destination patterns of bicyclists riding through the intersection areas studied."

Hunter et al. recommend the use of BLs "…where there is adequate width, in that BLs are more likely to increase the amount of bicycling than WCLs" (*91*).

Discussion: Grade separation for cyclists

In China, a country where bicycling is a very popular mode of transportation, the city of Beijing has provided grade separation for cyclists at more than 50 interchanges (Liu, Shen, and Ren, 1993; Burden, Wallwork and Guttenplan, 1994; as summarized by Hunter et al. (*91*)). Grade separation can effectively reduce the potential for conflicts between bicycles and motor vehicles at intersections. However, it is also very costly, so a number of less expensive at-grade options have been developed to enhance bicycle safety, such as those described in this section. For obvious reasons, these lower-cost alternatives are in wider use than grade separations.

Discussion: Offset or discontinue bike lanes at intersections

It is sometimes feasible, when a bicycle path must cross a street, to offset that crossing away from the regular intersection. This allows bicyclists a better view of motor vehicle traffic. Another option is the use of a dashed bike lane pavement marking stripe to guide cyclists in the curbside bike lane to the left of right-turning cars. This was done at one location in Cupertino, California (Grigg, 1978 as cited in (*91*)). Several state DOTs, including Florida, recommend that bike lanes be discontinued or dashed on the approach to an intersection, permitting bicycles and cars to merge (*91*). It is also desirable for right-angle bicycle crossings at intersections to allow for good sight lines.

Treatment: Raised painted bicycle crossings

Raised crossings for bicycles, some of which were marked with blue pavement, at signalized intersections in Denmark led to a 36% reduction in bicycle-motor vehicle crashes and a 57% reduction in the number of cyclists killed or severely injured (*94*). Sufficient details of the study were not available to verify sample sizes or statistical validity of these results.

Raised, painted bicycle crossings installed at 44 intersections in Gothenburg, Sweden had similar safety benefits. The traffic control in place at the intersections was not reported. After installation, the speed of motor vehicles making right turns went down by 35 to 40%, while bicycle speeds increased 10 to 15%. Based on a quantitative model, the calculated safety benefit of these two changes in speed was a 10% reduction in bicycle-motor vehicle crashes. A survey showed that bicyclists attributed a perceived 20% improvement in their safety to the raised and painted crossings. Experts who were also surveyed suggested a 30% safety enhancement, but Leden pointed out that the number of crashes were likely to increase because the improved crossing facilities had led to a 50% increase in bicycle usage (Leden, 1997 as cited by (*93*)).

The following year, researchers used a Bayesian approach to reevaluate findings from the Leden study (Garder, Leden, and Pulkkinen, 1998 (*61*)). This study was reviewed by Elvik and Vaa (2004) (*5*). It employed state-of-the-art Empirical Bayes methodology and was been rated as a high quality study. The standard error has been adjusted by a factor of 1.2, and the result is presented in Exhibit 4-90. However, the result is considered inconclusive based on the large standard error.

Exhibit 4-90: Effects on accidents of providing raised painted bicycle crossings at intersections (5)

Author, Date	Treatment/ Element	Setting	Intersection type & volume	Accident Type & Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa (2004)	Raised bicycle crossings	Not reported	Not reported	Bicycle accidents, injury	1.088	0.527

Another Swedish study based on a literature review, bicyclist interviews, and expert opinions found that adding a bicycle path at signalized intersections would cause a 40% increase in crash risk (Leden, Garder, and Thedeen, 1993 as cited in (*93*)).

In short, the research literature from Europe shows mixed results on the effects of raised bicycle crossings on bicycle safety at intersections. The true safety effect is not easy to determine from available research studies and may depend on the specific manner in which the treatments are installed, the behaviors of the motorists and bicyclists at the sites, driver expectation for cyclists, the countries where the treatments are applied (i.e., the road use culture), the visibility of cyclists at intersections, vehicle approach speeds and perhaps other factors.

4.3.4. Pedestrians and Bicyclists at Roundabouts [Future Edition]

In future editions of the HSM, this section may contain discussion of pedestrian and bicyclist accommodation specific to roundabout intersections. Potential resources are listed in Exhibit 4-91.

Exhibit 4-91: Potential resources on pedestrian and bicyclist safety at roundabouts

DOCUMENT
(*123*) Daniels, S., Nuyts, E., and Wets, G., "The Effects of Roundabouts on Traffic Safety for Bicyclists: An Observational Study", *Accident Analysis and Prevention*, 40 (2008), pp. 518-526.
(*120*) Rodegerdts, et al., "Roundabouts in the United States", *NCHRP Report* 572, TRB, (2007).
Dijkstra, Ir. A. 2004: Rotondes met vrijliggende fietspaden ook veilig voor fietsers? R-2004-14 (www.SWOV.nl/rapport/R-2004-14.pdf).
Building a True Community, a report from the Public Rights-of-Way Access Advisory Committee submitted to the Board in January 2001.
Accessible Rights-of-Way: A Design Guide, a guide the Board developed in cooperation with the Federal Highway Administration to provide advisory information until guidelines for public rights-of-way are developed

DOCUMENT
Accessible Pedestrian Signals, a Board report that provides a synthesis on current technology in accessible pedestrian signals, including a listing of devices and manufacturers in the U.S. and abroad, and a matrix comparing the features of each device. Note: A more recent synthesis of accessible pedestrian signal technologies developed through the National Cooperative Highway Research Program (NCHRP) is avaialble at www.walkinginfo.org/aps/.
Detectable Warnings: Synthesis of U.S. and International Practice, a Board-sponsored study on detectable warnings that surveys the state-of-the-art in the U.S. and abroad and summarizes the installation and effectiveness of various designs.
(Persaud, B. N., Retting, R. A., Garder, P. E., and Lord, D., "Observational Before-After Study of the Safety Effect of U.S. Roundabout Conversions Using the Empirical Bayes Method." Transportation Research Record, No. 1751, Washington, D.C., Transportation Research Board, National Research Council, (2001))
(Persaud, B. N., Retting, R. A., Garder, P. E., and Lord, D., "Crash Reduction Following Installation of Roundabouts in the United States." Arlington, Va, Insurance Institute for Highway Safety, (2000))
(Flannery, A. and Elefteriadou, L., "A Review of Roundabout Safety Performance in the United States." Las Vegas, Nev., Proc. 69th Annual Meeting of the Institute of Transportation Engineers , (1999))
(Ekman, L. and Hyden, C., "Pedestrian Safety in Sweden." FHWA-RD-99-091, McLean, Va., Federal Highway Administration, (1999))
(Leaf, W. A. and Preusser, D. F., "Literature Review on Vehicle Travel Speeds and Pedestrian Injuries Among Selected Racial/Ethnic Groups." DOT HS 908 021, Washington, D.C., National Highway Traffic Safety Administration, (1999))
(Robinson, D. L., "Accidents at Roundabouts in New South Wales." Road and Transport Research, Vol. 7, No. 1, Vermont South, Australia, ARRB Transport Research Ltd., (1998) pp. 3-12.)
(Brown, M., "The Design of Roundabouts - Volume 2." London, England, Transport Research Laboratory, Department of Transport, (1995),Brown, M., "The Design of Roundabouts - Volume 1." London, England, Transport Research Laboratory, Department of Transport, (1995))
(Schoon, C. and van Minnen, J., "The Safety of Roundabouts in The Netherlands." Traffic Engineering & Control, Vol. 35, No. 3, London, United Kingdom, Hemming Information Services, (1994) pp. 142-148.)
(Brude, U. and Larsson, J., "The Safety of Cyclists at Roundabouts: A Comparison between Swedish, Danish, and Dutch Results." Nordic Road and Transport Research, No. 1, Linköping, Sweden, Johnny Dahlgren Grafisk Produktion AB, (1997) pp. 23-25.)

4.3.5. Pedestrian and Bicyclist Traffic Control

At many locations, pedestrians depend on traffic signals for help in getting safely across the street. Several traffic control devices can be employed at intersections to direct pedestrians, such as crosswalk markings, pedestrian signal heads, push buttons, signs, and audible signals. Traffic controls may also be provided specifically for cyclists at popular cyclist locations.

This section will provide information available from the literature on traffic control devices related to pedestrians and cyclists at intersections. Pedestrian and bicycle treatments are discussed separately.

Pedestrian traffic control treatments and issues discussed in this section include:

- Install pedestrian signal heads at signalized intersections
- Type of pedestrian signal (solid or flashing WALK/DON'T WALK, or walking man/hand symbols)
- Install pedestrian countdown signals
- Provide audible and/or vibrotactile pedestrian signals
- Illuminated pedestrian push buttons

- Provide leading pedestrian interval (LPI)
- Automated Pedestrian Detectors
- Install innovative pedestrian traffic control devices
- Pedestrian safety at signalized intersections of different configurations
- Pedestrian-related signs
- Right-turn-on-red

Bicyclist traffic control treatments found in current literature and added to the discussion here are:

- Colored bicycle crossings
- Profiled pavement markings
- Advanced stop line (ASL) or bike box

Section 4.2 contains further details on intersection operations.

4.3.5.1. Pedestrian Traffic Control

The following discussion includes research related to signalization, signs, and markings, as they relate to pedestrian safety. Much of the information in this section related to pedestrians has been adapted from information from "A Review of Pedestrian Safety Research in the United States and Abroad" (*41*), in addition to other sources.

Exhibit 4-92: Resources examined to investigate the safety effect of pedestrian traffic control at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*95*) (Eccles, K. A., Tao, R., and Mangum, B. C., "Evaluation of Pedestrian Countdown Signals in Montgomery County, Maryland." Washington, D.C., 83rd Transportation Research Board Annual Meeting, (2004))	Before-and-after study to determine the effects of pedestrian countdown signals on both pedestrian and motorist behavior in Montgomery County, MD	Added to synthesis.
(*41*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research on pedestrians including the effect on pedestrian safety of traffic control.	Suggested by NCHRP 17-18(4). Much of the information in this section has been adapted from this document. Added to synthesis.
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Crashes at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies for accident mitigation at signalized intersections.	Limited discussion of pedestrian crashes. No additional information, not added to synthesis.
(Zegeer, C. V., Stutts, J., Huang, H., Cynecki, M. J., Van Houten, R., Alberson, B., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 10: A Guide for Reducing Crashes Involving Pedestrians." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies for pedestrian accident mitigation.	Not added to synthesis – similar information provided in Campbell (2004).
(*42*) Lord, D., "Synthesis on the Safety of Right Turn on Red in the United States and Canada." 82nd Transportation Research Board Annual Meeting, Washington, D.C., (2003)	Reviews various studies	Added to the synthesis

DOCUMENT	DESCRIPTION	COMMENT
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Synthesis of past research on a variety of treatments.	Not added to synthesis.
(Retting, R. A., Chapline, J. F., and Williams, A. F., "Changes in Crash Risk Following Re-timing of Traffic Signal Change Intervals." Accident Analysis and Prevention, Vol. 34, No. 2, Oxford, N.Y., Pergamon Press, (2002) pp. 215-220.)	Before/after study with control groups of crash experience at intersections with signal timing changes, particularly to change intervals.	Included in signal operations discussion. Not added to synthesis.
(Retting, R. A., Nitzburg, M. S., Farmer, C. M., and Knoblauch, R. L., "Field Evaluation of Two Methods for Restricting Right Turn on Red to Promote Pedestrian Safety." ITE Journal, Vol. 72, No. 1, Washington, D.C., Institute of Transportation Engineers, (2002) pp. 32-36.)	Evaluated two methods for restricting RTOR at urban intersections in Arlington, Virginia.	Not relevant to this section. Not added to synthesis.
(*43*) (Retting, R. A., Nitzburg, M. S., Farmer, C. M., and Knoblauch, R. L., "Field Evaluation of Two Methods for Restricting Right Turn on Red to Promote Pedestrian Safety." ITE Journal, Vol. 72, No. 1, Washington, D.C., Institute of Transportation Engineers, (2002) pp. 32-36.)	Driver behavioral data were collected and analyzed at 15 signalized intersections in Arlington, VA to evaluate time-specific RTOR-prohibition signs, and NTOR "When Peds are Present" signs	Added to synthesis.
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))	Summarizes various studies on pedestrian crossing treatments at uncontrolled intersections, signalized intersections, and mid-block signals	Suggested by NCHRP 17-18(4). No relevant information, not added to synthesis.
(*96*) (Huang, H. F. and Zegeer, C. V., "An Evaluation of Illuminated Pedestrian Push Buttons in Windsor, Ontario." FHWA-RD-00-102, McLean, Va., Federal Highway Administration, (2001))	Evaluates illuminated push buttons at four intersections in Windsor, Ontario.	Suggested by NCHRP 17-18(4). No AMFs. Added to synthesis.
(*97*) (Hughes, R., Huang, H., Zegeer, C. V., and Cynecki, M. J., "Evaluation of Automated Pedestrian Detection at Signalized Intersections." FHWA-RD-00-097, McLean, Va., Federal Highway Administration, (2001))	Before and after study, evaluated the effect of automated pedestrian detectors used in conjunction with push buttons on conflicts and inappropriate crossings in Los Angeles, CA, Phoenix, AZ, and Rochester, NY	Suggested by NCHRP 17-18(4). No AMFs. Added to synthesis.
(*109*) Nitzburg, M. and Knoblauch, R. L., "An Evaluation of High-Visibility Crosswalk Treatment - Clearwater Florida." *FHWA-RD-00-105*, McLean, Va., Federal Highway Administration, (2001)	Studied the behavioral effects of a novel overhead illuminated crosswalk sign and high-visibility ladder style crosswalk on narrow low-speed roadways in Clearwater, FL	Added to synthesis.
(*108*) Huang, H. F., Zegeer, C. V., Nassi, R., and Fairfax, B., "The Effects of Innovative Pedestrian Signs at Unsignalized Locations: A Tale of Three Treatments." *FHWA-RD-00-098*, McLean, Va., Federal Highway Administration, (2000)	Several innovative pedestrian devices used in conjunction with marked crosswalks at unsignalized locations were evaluated	Added to synthesis.
(King, M. R., "Calming New York City Intersections." Dallas, Tex., Urban Street Symposium Conference Proceedings, (2000))	Evaluated the effect of leading pedestrian intervals on crashes at 26 intersections in New York City; used a before and after study	Suggested by NCHRP 17-18(4). No AMFs. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*98*) (Van Houten, R., Retting, A. R., Farmer, C. M., and Van Houten, J., "Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections." Transportation Research Record, No. 1734, Washington, D.C., Transportation Research Board, National Research Council, (2000) pp. 86-92.)	Evaluated the effect on safety of using a three-second leading pedestrian interval at three urban intersections; used pedestrian behavior and conflicts	Suggested by NCHRP 17-18(4). No AMFs. Added to synthesis.
(Ekman, L. and Hyden, C., "Pedestrian Safety in Sweden." FHWA-RD-99-091, McLean, Va., Federal Highway Administration, (1999))	Synthesis of pedestrian safety practices in Sweden.	Not relevant to this section. Not added to synthesis.
(*99*) (Leonard, J., Juckes, M., and Clement, B., "Behavioural Evaluation of Pedestrians and Motorists towards Pedestrian Countdown Signals." Laval, Quebec, Canada, Dessau-Soprin Inc, (1999))	Evaluated the effect on pedestrian safety of pedestrian countdown signals at intersection using pedestrian and motorist behavior	Suggested by NCHRP 17-18(4). No AMFs. Added to synthesis.
(Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. H., and Pein, W. E., "Bicycle Lanes Versus Wide Curb Lanes: Operational and Safety Findings and Countermeasure Recommendations." FHWA-RD-99-035, McLean, Va., Federal Highway Administration, (1999))	Summary of literature on a number of countermeasures developed and tested in the U.S. and abroad to facilitate the safe passage of bicyclists through intersections	Same information as Hunter et al. (1999) below. Not added to synthesis.
(Hummel, T., "Dutch Pedestrian Safety Research Review." FHWA-RD-99-092, McLean, Va., Federal Highway Administration, (1999))	Synthesis of pedestrian safety practices in the Netherlands.	No AMFs. Not added to synthesis.
(Van Houten, R. and Malenfant, J. E. L., "Canadian Research on Pedestrian Safety." FHWA-RD-99-090, McLean, Va., Federal Highway Administration, (1999))	Synthesis of pedestrian safety practices in Canada.	No AMFs. Not added to synthesis.
(Jensen, S. U., "Junctions and Cyclists." Barcelona, Spain, Proc. Velo City '97 - 10th International Bicycle Planning Conference, (1997))	Evaluation of raised crossings for bicycles, some of which were marked with blue pavement, at signalized intersections in Denmark	Limited information added to Section 4.3.3. No AMFs.
(Retting, R. A., Van Houten, R., Malenfant, L., Van Houten, J., and Farmer, C. M., "Special Signs and Pavement Markings Improve Pedestrian Safety." ITE Journal, Vol. 66, No. 12, Washington, D.C., Institute of Transportation Engineers, (1996) pp. 28-35.)	Observed three signalized intersections before and after prompts for pedestrians to look for turning vehicles (special signs and pavement markings) were implemented	Not relevant to this section. Not added to synthesis.
(*100*) (Lord, D., "Analysis of Pedestrian Conflicts with Left Turning Traffic." Transportation Research Record 1538, Washington, D.C., Transportation Research Board, National Research Council, (1996))	Studied pedestrian conflicts with left-turning vehicles at T-intersections and four-leg intersections	Limited qualitative information added to synthesis. No AMFs.
(*101*) (Clark, K. L., Hummer, J. E., and Dutt, N., "Field Evaluation of Fluorescent Strong Yellow-green Pedestrian Warning Signs." Transportation Research Record 1538, Washington, DC, Transportation Research Board, National Research Council, (1996))	Experimented with using a fluorescent yellow-green sign to warn drivers of pedestrians	Limited qualitative information added to synthesis. No AMFs.
(*74*) (Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	Report to Congress	Limited qualitative information added to synthesis. No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
(Herrstedt, L., Nielsen, M. A., Agustson, L., Krogsgaard, K. M. L., Jorgensen, E., and Jorgensen, N. O., "Safety of Cyclists in Urban Areas: Danish Experiences." Copenhagen, Denmark, Danish Road Directorate, (1994))	Study done in Denmark of profiled pavement markings	Not added to synthesis. No AMFs.
(Radwan, A. E. and Wing, D., "Safety Effects of Traffic Signal Installations: State of the Art." FHWA/AZ-87/809, Phoenix, Arizona Department of Transportation, (1987))	Review of signal installations and impact on accident patterns, frequency and severity, including pedestrians.	No AMFs, not added to synthesis.
(*103*) (Zaidel, D. M. and Hocherman, I., "Safety of Pedestrian Crossings at Signalized Intersections." Transportation Research Board 1141, Washington, D.C., Transportation Research Board, National Research Council, (1987))	Evaluated the safety effects of concurrent and exclusive signal timing, as opposed to no pedestrian interval or pedestrian signal head. A total of 320 signalized intersections	Added to synthesis.
(*44*) (Zegeer, C. V. and Cynecki, M. J., "Evaluation of Countermeasures Related to RTOR Accidents that Involve Pedestrians." Transportation Research Record 1059, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 24-34.)	Collected observational data on more than 67,000 drivers at 110 intersections in Washington, D.C., Dallas, Austin, Detroit, Lansing, and Grand Rapids, studied motorist violations of NO TURN ON RED (NTOR) signs and crashes with pedestrians	Added to synthesis. No AMFs.
(*104*) (Robertson, H. D. and Carter, E. C., "The Safety, Operational, and Cost Impacts of Pedestrian Indications at Signalized Intersections." Transportation Research Record 959, Washington, D.C., Transportation Research Board, National Research Council, (1984))	Literature review, an analysis of pedestrian crashes, a delay analysis, and a benefit-cost analysis of pedestrian signal indications.	Limited qualitative information added to synthesis. No AMFs.
(*105*) (Zegeer, C. V., Opiela, K. S., and Cynecki, M. J., "Pedestrian Signalization Alternatives." FHWA/RD-83/102, Washington, D.C., Federal Highway Administration, (1983))	Analyzed data from 1,297 signalized intersections involving a total of 2,081 pedestrian crashes in 15 U.S. cities (same as Zegeer et al., 1982)	Added to synthesis.
(*45*) (Clark, J. E., Maghsoodloo, S., and Brown, D. B., "Public Good Relative to Right-Turn-on-Red in South Carolina and Alabama." Transportation Research Record 926, Washington, D.C., Transportation Research Board, National Research Council, (1983) pp. 24-31.)	Evaluated the effects of the change in the RTOR laws in South Carolina and Alabama on the proportion of right turn and pedestrian crashes	Added to synthesis.
(*106*) (Zegeer, C. V., Opiela, K. S., and Cynecki, M. J., "Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents." Transportation Research Record 847, Washington, D.C., Transportation Research Board, National Research Council, (1982) pp. 62-72.)	Analyzed data from 1,297 signalized intersections involving a total of 2,081 pedestrian crashes in 15 U.S. cities	Added to synthesis.
(Short, M. S., Woelfl, G. A., and Chang, C. J., "Effects of Traffic Signal Installation On Accidents." Accident Analysis and Prevention, Vol. 14, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 135-145.)	Before/after study of 31 newly signalized intersections in Milwaukee, including analysis of pedestrian and bicycle crashes.	Not relevant to this section. Not added to this synthesis.
(*46*) (Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M., "The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents." Journal of Safety Research, Vol. 13, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 45-55.)	Examined the effects of RTOR on pedestrian safety	Limited information added to synthesis. No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))	Discusses some design features which are appropriate including pedestrian and bicycle facilities.	Not added to synthesis. No AMFs.
(Mueller, E. A. and Rankin, W. W., "Pedestrians." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 8, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Synthesis of older literature on pedestrian safety.	Not added to synthesis.

Discussion: Install pedestrian signal heads at signalized intersections

The most comprehensive study of pedestrian signal heads was performed by Zegeer et al. (1982, 1983), who analyzed data from 1,297 urban signalized intersections involving a total of 2,081 pedestrian crashes in 15 U.S. cities (*106,105*). The four pedestrian timing patterns used at the 1,297 signalized intersections in the study are summarized in Exhibit 4-93. Marked crosswalks existed at nearly all of the intersections. Of the 1,297 intersections, 508 did not have pedestrian signal heads (i.e., WALK – DON'T WALK).

Exhibit 4-93: Pedestrian signal timing patterns studied by Zegeer et al. (106,105)

Pedestrian timing pattern	Study intersections	Description
Concurrent (standard)	658 (50.7%)	Gives pedestrians a WALK interval at the same time that parallel traffic has a green light. During this phase, vehicles may also turn right or left across the pedestrian's path when safe to do so. Concurrent timing is the type most often used in the U.S.
None	508 (39.2%)	Pedestrians are expected to comply with the vehicular signal heads.
Exclusive	109 (8.4%)	Gives pedestrians a phase during each signal cycle where motor traffic is stopped in all directions so that pedestrians may take advantage of the interval to cross the street. A variation of this timing strategy is the "scramble" or "Barnes Dance" phase, which allows pedestrians to cross diagonally through the intersection as well as across the intersecting roadways
Early release or Late release	22 (1.7%)	Early: Gives pedestrians a head start in each cycle before allowing motorists to make right or left turns Late: Makes pedestrians wait to cross until after vehicles have turned

The Zegeer team found a statistically significant relationship between increased pedestrian crashes and factors such as higher pedestrian and vehicle volumes, two-way (vs. one-way) roads, wider streets, higher bus use, and greater percentage of turning movements. Compared with traffic signals without pedestrian signal heads, concurrent timing had no statistically significant effect on pedestrian crashes. Exclusive timing produced statistically significant fewer (about half) of the pedestrian crashes as concurrent timing or signals with no pedestrian signals. However, this was only true at locations with pedestrian volumes of more than 1,200 people per day (*106*,*105*). There was insufficient sample size (22 sites) of early release and late release signal timing to determine the safety effect of those timing schemes. The implementation of a Leading Pedestrian Interval is discussed later in this section.

Zegeer et al. controlled for the effects of pedestrian volume, traffic volume, intersection geometrics, etc. The results of the study are summarized in Exhibit 4-94.

Zegeer et al. suggest the following possible reasons that concurrent signal timing was not found to be effective in reducing pedestrian crashes (*106*,*105*):

- Many pedestrians misunderstand the meaning of signal messages such as the flashing DON’T WALK, which is intended to alert pedestrians that they should not enter the street now but should finish crossing if they’ve already started;
- Some pedestrians have the incorrect assumption that a WALK interval stops traffic in all directions, including turns;
- Many pedestrians do not comply with pedestrian signals (e.g., 65.9% of the pedestrians at 64 intersection approaches were observed to began crossing the street during the flashing or steady DON’T WALK phase);
- Many pedestrians seem reluctant to use the push buttons that activate pedestrian signals (only 51.3% of all pedestrians in the study used the button to activate the crossing signal).

Exhibit 4-94: Summary of effects of pedestrian signal timing on pedestrian crashes

Comparison	Dependent Variable (per year)	Adjusted Means (Sample Sizes in Parentheses)	Significant Difference (0.05 level)	Level of Significance
All Ped. Signal Alternatives	Mean Pedestrian Crashes	No Ped. Signal: 0.36 (508) Concurrent: 0.40 (658) Exclusive: 0.22 (109) Other: 0.38 (22)	Yes	0.001
	Mean Pedestrian Turning Crashes	No Ped. Signal: 0.13 (508) Concurrent: 0.17 (658) Exclusive: 0.01 (109) Other: 0.20 (22)	Yes	0.001
No. Ped. Signal Indication vs. Concurrent Ped. Signal Timing	Mean Pedestrian Crashes	No Ped. Signal: 0.36 (508) Concurrent: 0.40 (658)	No	0.130
	Mean Pedestrian Turning Crashes	No Ped. Signal: 0.12 (508) Concurrent: 0.15 (658)	Yes	0.048

Comparison	Dependent Variable (per year)	Adjusted Means (Sample Sizes in Parentheses)	Significant Difference (0.05 level)	Level of Significance
No. Ped. Signal Indication vs. Exclusive Ped. Signal Timing	Mean Pedestrian Crashes	No Ped. Signal: 0.33 (508) Exclusive: 0.15 (109)	Yes	0.001
	Mean Pedestrian Turning Crashes	No Ped. Signal: 0.11 (508) Exclusive: 0.00 (109)	Yes	0.001
Concurrent Ped. Signal Timing vs. Exclusive Ped. Signal Timing	Mean Pedestrian Crashes	Concurrent: 0.43 (658) Exclusive: 0.27 (109)	Yes	0.001
	Mean Pedestrian Turning Crashes	Concurrent: 0.17 (658) Exclusive: 0.03 (109)	Yes	0.001

For each comparison, control variables were: Pedestrian Volume (AADT), Total Traffic Volume (AADT), Street Operation (One-Way/Two-Way), Ped. Signal Alternatives

Based on their research, Zegeer et al. recommended that highway agencies should not automatically install pedestrian signals at all locations that have traffic signals. Each site should be evaluated in terms of cost versus effectiveness (*106,105*). However, the authors affirm the need for pedestrian signals at certain types of locations including school crossings, on wide streets, or places where the vehicular traffic signals are not visible to pedestrians.

Research in Israel (*103*) has evaluated the safety effects of concurrent and exclusive signal timing, as opposed to no pedestrian interval. A total of 320 signalized intersections in Tel Aviv, Jerusalem, and Haifa were included in this study, with analysis of 1,310 pedestrian accidents and 5,132 vehicle crashes. Higher rates of pedestrian crashes were found at intersections with the higher pedestrian and vehicle volumes, as well as at more complex intersections (i.e., the most legs or potential points of conflict). The type of signal timing provided for pedestrians had only a slight effect on pedestrian crashes and no effect on vehicle injury crashes, especially where vehicle volumes were low (less than 18,000 ADT). Intersections with exclusive phases for pedestrians had fewer crashes where vehicle and pedestrian volumes were higher (*103*). These results concur with the results of Zegeer et al. (1982, 1983).

Using a literature review, an analysis of pedestrian crashes, a delay analysis, and a benefit-cost analysis, a 1984 study by Robertson and Carter found that pedestrian signal indications reduce pedestrian crashes at some intersections, have little or no effect at others, and may actually increase crashes at yet other sites (*104*). The presence of pedestrian signals in itself did not have a statistically significant effect on pedestrian and vehicle delay, but the signal timing scheme had a major influence on delay. As a result of this study, the authors suggested further study to identify the types of intersections where pedestrian signals would be most effective. AMFs could not be derived from the study results.

Discussion: Provide leading pedestrian interval (LPI)

Van Houten et al. studied the introduction of a three-second leading pedestrian interval (LPI) at three signalized intersections in downtown St. Petersburg, Florida. Using WALK/DON'T WALK signal heads that were automatically coordinated with the signal timer (i.e., did not require push buttons), signal phasing at the intersections were programmed to release pedestrian traffic three seconds before vehicle traffic. A one-second all-red interval was used at all intersections (*98*). Based on observations of pedestrians older than age 12 on weekdays between 8:30 am and 5:00 pm (excluding periods of heavy rain), logistic regression models were used to estimate the effects of the LPI. The models included vehicle-pedestrian conflicts, pedestrian yielding, time, site location, and pedestrian age (senior vs. non-senior). Van Houten et al. conclude that the introduction of a three-second LPI "reduced conflicts between pedestrians and turning vehicles, reduced the incidence of pedestrians yielding the right-of-way to turning vehicles, and made it somewhat easier for pedestrians to cross the street by allowing them to occupy the crosswalk before turning vehicles were permitted to enter the intersection" (pg 88, (*98*)). Note that accessible pedestrian signals are needed for pedestrians who don't use visual cues. A crash analysis was not performed as part of the study.

Discussion: Illuminated pedestrian push buttons

When pedestrians come to an intersection where a push button is necessary to activate the WALK phase on a crossing signal, they might wonder whether the button has already been pushed and whether or not it is working. If they push the button and there is a delay before the WALK phase illuminates, they might think the system is broken and begin crossing the street too soon, while DON'T WALK is still showing. One solution to this problem is the illuminated push button, which has a light that comes on to show that the WALK phase has indeed been called and will soon be displayed.

A study by Huang and Zegeer (2000) looked at the effects of illuminated push buttons on pedestrian behavior (*96*). The authors found that illuminated push buttons made no statistically significant difference in crossing behavior, including how often the pedestrian phases were activated and how many people actually pushed the button or complied with the WALK message. The lighted buttons also had no significant influence on pedestrian behaviors such as running, aborted crossings, and hesitation prior to entering the street. Before the illuminated push buttons were installed, 17% of pedestrians pushed the button; afterwards, only 13% did so. Both before and after installation of the lighted device, the button was pushed 32% of the time by at least one person in each group. Among people who pushed the button when parallel traffic had the red light, the percentage that actually complied with the WALK phase was 67.8% with the illuminated type of push button and 72.3% without—a majority of pedestrians in either case (*96*).

Discussion: Automated pedestrian detectors

Another type of device created to assist people in crossing the street is the automated pedestrian detection system, which senses the presence of people standing at the curb (waiting to cross the street) and then mechanically activates the WALK signal without any action required from the pedestrian to push a button. Another feature of the detectors at some locations is that another sensor can be aimed to monitor slower-walking pedestrians in the street, so it will extend the clearance interval until the pedestrian is safe on the other side.

In 2000, Hughes, Huang, Zegeer, and Cynecki tried to determine whether these automated systems combined with standard pedestrian push buttons could reduce pedestrian-vehicle conflicts and reduce the number of people entering the roadway during the DON'T WALK (or flashing DON'T WALK) display (*97*). Videos were taken before and after installation of the automated systems at intersections in Los Angeles, Phoenix, and Rochester, NY, with results showing a statistically significant reduction in pedestrian-vehicle conflicts as well as the percent of pedestrian crossings initiated during the DON'T WALK phase. Both infrared and microwave sensors were tested, with no significant differences found. However, field testing of the microwave equipment in Phoenix suggested a need for fine turning the detection zone in order to reduce false and missed calls.

Discussion: Type of pedestrian signal (solid or flashing WALK/DON'T WALK, or walking man/hand symbols)

Several behavioral studies in the U.S. have found pedestrian comprehension with signals to be a challenge. Furthermore, studies differ somewhat on the effects of pedestrian signals (i.e., WALK/ DON'T WALK) on pedestrian behavior.

Since earlier research had indicated that pedestrians often misunderstand the meaning of a flashing DON'T WALK signal (i.e., the pedestrian clearance interval), the Zegeer et al. team developed and field-tested several alternatives. One involved adding a third pedestrian signal message – a steady yellow DON'T START – to the standard WALK and flashing DON'T WALK signal. This three-message signal produced a statistically significant reduction in pedestrian violations and conflicts at three out of four test sites (urban signalized intersections with moderate to high pedestrian volumes) and was therefore recommended for additional tests. On the other hand, it was found that displaying a steady DON'T WALK message during the clearance and pedestrian prohibition intervals was no more effective than the flashing DON'T WALK, and therefore, was not recommended (*106*).

Many people appear to not understand the exact meaning of pedestrian signals and markings or the relevant legalities. Survey data taken from 48 states in 1995 resulted in the following responses related to crosswalks (Tidwell et al., 1995 as cited in (*41*)):

- 86 to 94% of the respondents said that pedestrians should cross the street at intersections or marked midblock crossings;
- 92 to 97% understood that motorists should yield to pedestrians in a marked crosswalk;
- 79 to 87% knew that RTOR vehicles must yield the right-of-way to people in a crosswalk;
- 59 to 61% were unaware that drivers are not obligated to stop when someone is waiting on the sidewalk to cross the street;
- 42 to 46% mistakenly think that a DON'T WALK message means that the pedestrian should return to the curb where the crossing began;
- 47% incorrectly believe that a WALK signal means there will be no conflicts with turning vehicles.

In an observational study (Petzold, 1977), compliance with pedestrian signals was analyzed at six intersections in Washington, D.C., San Francisco, and Oakland, CA (as summarized by Campbell et al. (*41*)). At the four intersections that had a flashing WALK signal to indicate the WALK phase, a total of 550 people were observed crossing the street. The other two intersections had a steady WALK signal to indicate the WALK phase; and 139 pedestrians were observed using these two crossings. No difference was found in how people used the flashing versus steady WALK signals. In fact, it was noted that many of the observed pedestrians paid very little attention to the signal. The study also found that most pedestrians do not understand the meaning of the flashing WALK and flashing DON'T WALK phases. Petzold noted that symbols such as the walking person and upheld hand were more readily comprehended than word messages on pedestrian signals (*41*). Another study cited by Campbell et al. (Palamarthy et al., 1994) found that only half of the pedestrians observed pushed the button to activate the WALK signal (*41*).

Another study summarized by Campbell et al. that compared the behavior of pedestrians relative to flashing versus solid WALK signals was conducted in Massachusetts (Sterling, 1974) (*41*). At these locations, selected for their high volume of both pedestrian and motor traffic, the signals were vehicle-actuated and had a fixed length for the pedestrian phase. It was found that 29% of pedestrians at intersections with a flashing WALK signal crossed the street legally, whereas 51% of pedestrians at intersections with a steady WALK signal made legal crossings. A conflict between pedestrian and vehicle occurred in 6% of the crossings at the intersections with the steady WALK signal, as opposed to conflicts occurring in 8% of the crossings at the intersections with a flashing WALK indication, which was found by Sterling to be a statistically significant difference (*41*).

Mortimer (1973) evaluated the behavior of 3,200 pedestrians who were observed crossing the street at 24 signalized intersections in Detroit, MI (as noted in (*41*)). Half of the sites had standard pedestrian signals; the others did not have pedestrian signals, only vehicular signals. There were 4% fewer pedestrians starting to cross on the amber/DON'T WALK phase at the crossings with pedestrian signals, than at locations without pedestrian signals. There were 20% more people arriving at the far side of the crossing on the green/WALK phase at sites with pedestrian signals than at locations without pedestrian signals (*41*). In short, Mortimer found some improvement in pedestrian behavior (i.e., fewer pedestrians in the crosswalk at the end of the WALK/green phase when pedestrian signals were present).

In 1967, Fleig and Duffy observed people crossing the street at one signalized intersection in Brooklyn, NY, where pedestrian signal heads had been installed (*41*). Along with this behavioral study, the researchers did a before -after comparison of crashes at 11 other locations where pedestrian signals were installed. No statistically significant differences were found in crashes at the 11 comparison sites or behaviors at the study site before and after installation of pedestrian signal heads.

Discussion: Install pedestrian countdown signals

In an effort to determine the effects of pedestrian countdown signals on both pedestrian and motorist behavior, a before-after study was conducted at five intersections (with 4 crosswalks per intersection, or 20 crosswalks) in Montgomery County, MD, where these signals were installed (*95*). Countdown signals, which are used in conjunction with standard pedestrian signal indications, provide the pedestrian with information about how much time remains to safely cross the street. A survey conducted as part of the study done in Maryland revealed that most pedestrians were aware of the countdown signal and 62.6% understood its meaning. Observational data gathered at the five intersections showed that the countdown signals had mixed effects on pedestrian behavior. At 2 of the 20 crosswalks observed, there was a statistically significant decrease in the number of pedestrians who entered on the WALK indication (i.e., more pedestrians began walking during the flashing or solid DON'T WALK indication). However, at 6 of the 20 crosswalks, there was a statistically significant increase (i.e., more pedestrians were correctly entering on the WALK indication).

The researchers also observed the number of phases during which pedestrians were still in the intersection when conflicting traffic was released; none of the intersections experienced a statistically significant increase in this measure during the after-installation phase (i.e., there was no increase in the number of phases in which a pedestrian was still in the crosswalk when conflicting traffic was released). At 4 of the 5 intersections, there were statistically significantly fewer pedestrian-motor vehicle conflicts after the countdown signals were installed (*95*).

Vehicle approach speeds were also observed during the Eccles et al. study. The authors found that the countdown signals had no effect on approach speeds during the pedestrian clearance interval (i.e., the flashing DON'T WALK when the countdown was displayed) (*95*).

Leonard et al. evaluated pedestrian and motorist behavior after the addition of a countdown signal to conventional pedestrian signal heads (i.e., Hand/Man or Walk/Don't Walk) in Monterey, California (*99*). The study took place at two signalized urban intersections; observations were conducted over a four-day period of 760 pedestrians. Overall, it was found that 83% of pedestrians started at the beginning of the pedestrian phase and completed the crossing during the phase. Leonard et al. conclude that "pedestrian countdown signals do not represent any significant safety hazards" (pg 16, (*99*)). The study did not review conflicts or accidents.

No AMFs could be developed for pedestrian countdown signals.

Discussion: Install innovative pedestrian traffic control devices

To address identified problems related to pedestrian traffic controls, such as confusion about the meaning of signal messages, Zegeer et al. (1982) developed and tested alternative methods for warning pedestrians and/or motorists of potential conflicts between pedestrians and turning vehicles at intersections (*105*). The devices were evaluated several months after installation. Long-term effects (i.e., after several years) were not studied. These novel devices were field tested at locations in Washington, D.C., Milwaukee, Detroit, Ann Arbor, and Saginaw, MI, with the following results:

- A sign reading YIELD TO PEDESTRIAN WHEN TURNING (red and white triangle, 36 inches on each side) reduced conflicts between pedestrians and turning vehicles.

- A black-on-yellow warning sign that said PEDESTRIANS WATCH FOR TURNING VEHICLES statistically significantly decreased conflicts between turning vehicles and pedestrians.
- At two locations where pedestrian violations (such as crossing against the signal) had not been problematic, a sign explaining the pedestrian signal had no detectable effect. However, at two sites with a history of serious pedestrian violations, the signal explanation sign did increase pedestrian compliance and reduced conflicts with turning vehicles.
- Four sites in three different cities were used to test a device for warning pedestrians about vehicles that were turning and/or possibly running red lights. This device consisted of a three-section signal that displayed the message WALK WITH CARE during the crossing interval. This signal was found to statistically significantly reduce pedestrian signal violations as well as conflicts with turning vehicles.

In another study, several innovative pedestrian devices used in conjunction with marked crosswalks at unsignalized locations were evaluated in terms of improved crosswalk visibility and motorist yielding behavior (*108*). The three devices were: an overhead CROSSWALK sign (Seattle, WA); pedestrian safety cones reading STATE LAW—YIELD TO PEDESTRIANS IN CROSSWALK IN YOUR HALF OF ROAD (NY State and Portland, OR); and pedestrian-activated STOP FOR PEDESTRIAN IN CROSSWALK overhead signs (Tucson, AZ). The signs were tested in locations with a variety of traffic and roadway conditions.

Both the safety cones used in New York and the overhead CROSSWALK signs in Seattle resulted in more drivers stopping for pedestrians, and one of the pedestrian-activated signs in Tucson increased motorists' yielding behavior. The signs in Seattle and Tucson decreased the instances where people had to run, hesitate, or abort an attempt to cross the street. None of the signs seemed to influence whether or not pedestrians crossed in the crosswalk (*108*).

Based on their findings, Huang et al. concluded that these signs alone would not ensure that drivers slow down and yield to people crossing the street; instead, pedestrian safety devices need to be supplemented with education and enforcement. Ultimately, many problems could be forestalled by designing "friendlier" pedestrian environments in the first place (*108*).

Nitzburg and Knoblauch (2000) studied the behavioral effects of a novel overhead illuminated crosswalk sign and high-visibility ladder style crosswalk on narrow low-speed roadways in Clearwater, FL (*109*). With these features in place, motorist yielding to pedestrians went up a significant 30 to 40% during the daytime, with a smaller increase at night (8%). The number of pedestrians who used the crosswalk rose by 35%. There was no observable change in pedestrian overconfidence, running, or conflicts. In conclusion, it was found that pedestrian and motorist behavior was positively affected by high-visibility crosswalk treatments on narrow low-speed roadways such as those included in this study; additional research is needed to determine their effectiveness on wider streets with higher speed limits (*109*).

Discussion: Pedestrian safety at signalized intersections of different configurations

A 1996 study confirmed earlier findings that more pedestrian conflicts with left-turning vehicles occur at T-intersections than at standard four-leg intersections (*100*). This is perhaps caused by the fact that a motorist turning left at a T-intersection does not have to wait for oncoming traffic and therefore might have no reason to hesitate before turning. In this scenario, the car could strike a person who has started crossing the street at the same moment that the turn was initiated. At four-leg intersections, on the other hand, motorists sometimes have to wait for oncoming vehicles to pass by, which gives pedestrians the equivalent of an early release timing pattern.

Discussion: Pedestrian-related signs

State and local agencies employ a variety of pedestrian-related signs, which fall into three categories:

- Regulatory signs, such as PEDESTRIANS PROHIBITED, WALK ON LEFT FACING TRAFFIC, NO HITCHHIKING;
- Warning signs like the advance pedestrian crossing sign and the school warning sign;
- Guide signs, which provide travel information or directions to walkways, trails, overpasses, or other pedestrian facilities.

Both the MUTCD (*17*) and the Traffic Control Devices Handbook (*29*) contain criteria for the design and placement of pedestrian-related signs. Using the experience of 48 state and local agencies, a study conducted in 1988 for the Transportation Research Board summarizes traffic and roadway conditions where various signs are most or least effective (*110*). The study did not quantify the safety effect of signage, and the results of the study are not repeated here.

In 1996, Clark et al. experimented with using a fluorescent yellow-green sign to warn drivers of pedestrians (*101*). The use of this new sign was associated with increased numbers of cars that slowed down or stopped for pedestrians, although there was no decrease in conflict events.

Discussion: Permit Right-Turn-On-Red (RTOR)

A study by Lord in 2003 reported that New York City and the Province of Quebec were the only places in North America that did not allow motorists to make a right turn on red (RTOR) at signalized intersections. In the year 2000, Quebec's Ministry of Transportation (MTQ) sponsored this study aimed at finally ending the quarter-century-old debate as to whether or not to permit RTOR (*42*). Elements of this study included analysis of crash statistics from Canada and the United States, a literature review, expert survey, and a two-part pilot study described below. One issue mentioned several times in Lord's paper outlining the MTQ study is the lack of adequate data related to RTOR crashes (*42*).

The two-part pilot study was initiated in the spring of 2001. Driver behavior was observed at 26 sites in the Province of Quebec where RTOR was authorized for a period of nine months. The second part of the pilot study involved collecting data from a number of U.S. and Canadian agencies concerning the effect that RTOR had on safety and on traffic operations (*42*).

Lord found that, in most cases, RTOR does not pose a danger to motorists, cyclists, or pedestrians. Lord reported that pedestrian crashes involving a RTOR maneuver make up less than 1% of all reported accidents in the U.S. and Canada, and the crashes that do occur are usually not severe. Many of the transportation experts and researchers who were surveyed for this study do not consider RTOR to be a safety problem (*42*).

Exhibit 4-94 shows that permitting RTOR increases pedestrian and bicycle crashes based on a study by Preusser et al. (*46*). Exhibit 4-94 displays the results of individual data sets supplied by 4 different jurisdictions (New York State (except New York City), Wisconsin, Ohio, and New Orleans) as well as the result of combining the AMFs and standard errors together. The index of effectiveness values (AMFs) were calculated from the data supplied by Preusser et al.

Preusser et al. indicate the mean values shown have been adjusted to account for seasonal differences but does not indicate if volume increases were accounted for. However, no further adjustments were made on the AMFs calculated from the data.

A method correction factor of 2.2 was used to adjust the standard error values calculated from the data, based on the use of accident frequencies and non-EB methodologies. Discussion of the impact on other types of crashes is found in Section 4.2.2.2.

Exhibit 4-95: AMFs for Pedestrian and Bicycle Crashes for Permitting Right-Turn-On-Red (46)

Author, date	**Treatment/ element**	**Setting**	**Intersection type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New York)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.429	0.243
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Wisconsin)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	2.075	0.512
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Ohio)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.574	0.306
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New Orleans)	Signalized Intersections, volume not reported	Pedestrian Crashes, All Severities	1.813	0.881
				Combined	**1.567**	**0.175**

Author, date	**Treatment / element**	**Setting**	**Intersection type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Preusser et al., 1982	Permit right-turn-on-red	Not reported (New York State)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.820	0.315
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Wisconsin)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.726	0.524
Preusser et al., 1982	Permit right-turn-on-red	Not reported (Ohio)	Signalized Intersections, volume not reported	Bicycle Crashes, All Severities	1.798	0.525
				Combined	**1.796**	**0.240**

In 1994, NHTSA (Compton and Milton) reported to Congress that 0.2% of all fatal pedestrian and bicycle accidents result from RTOR (*74*).

In 1986, Zegeer and Cynecki collected observational data on more than 67,000 drivers at 110 intersections in Washington, D.C., Dallas, Austin, Detroit, Lansing, and Grand Rapids, looking for links between motorist violations of NO TURN ON RED (NTOR) signs and the related crashes with pedestrians (*44*). Analysis of the data showed that 3.7% of all drivers making a right-turn violated the NTOR signs. When given an opportunity to violate the NTOR sign (i.e., being the first car in line at a signalized intersection with no pedestrians in front of them and no cars coming from the left), 21% of the drivers ignored the NTOR signs.

Furthermore, according to Zegeer and Cynecki, 23.4% of all RTOR violations create a conflict with a pedestrian. Where RTOR is permitted, 56.9% of drivers do not come to a complete stop before turning, compared with 68.2% who fail to do so at STOP-controlled intersections. One suggested reason for the higher violation rate at the latter is that stop-sign intersections may be more conducive to either a rolling stop or no stop at all due to lower side street volumes and pedestrian activity than most signalized locations (*44*).

In a later phase of the study, Zegeer and Cynecki developed 30 potential countermeasures to enhance pedestrian safety at intersections permitting RTOR, where seven of these countermeasures were tested at 34 intersections in six cities in the U.S. Motorist violations and pedestrian-vehicle conflicts related to both RTOR and RTOG (right turn on green) were used as measures of effectiveness (*44*). Results included the following:

- NTOR signs with a red ball were more effective than standard black-and-white ones.
- An offset stop bar increased compliance in making a full stop before turning at RTOR locations and also lessened conflicts with traffic on cross streets.
- The more costly electronic NTOR/black-out sign used only during school crossing periods or other critical times was slightly more effective than the regular NTOR sign.
- Drivers were more likely to comply with the RTOR restriction if it was limited to peak pedestrian periods rather than imposed full-time.
- In areas with moderate or low RTOR volumes, an alternative NTOR WHEN PEDESTRIANS ARE PRESENT sign was effective at intersections with low to moderate volumes of RTOR vehicles.
- In general, the likelihood of a RTOG accident was found to be greater than that of a RTOR accident, based on conflict data.

During the mid-1970’s, a number of states in the eastern portion of the United States adopted the “permissive” type of RTOR that was already common out west. The “Western” approach to RTOR allows this maneuver at all locations that are not otherwise marked by a prohibitory sign. Of course, motorists are expected to stop and yield to pedestrians, bicyclists, and oncoming vehicles prior to making a Western RTOR. A study by Preusser et al. (1982) of several eastern locations revealed statistically significant increases in pedestrian and bicyclist crashes with right-turning vehicles after the Western RTOR was introduced (*46*). Comparison of computerized accident data from the periods before and after implementation of the Western RTOR rule showed the following increases in accident rates:

- 43% for pedestrian accidents and 82% for bicycles in New York State;

- 107% for pedestrians and 72% for bicycles in Wisconsin;
- 57% for pedestrians and 80% for bicycles in Ohio; and
- 82% for pedestrians in New Orleans.

It should be remembered that these percentages are increases in very small numbers, since RTOR-pedestrian crashes are very rare.

A second part of this study involved analysis of actual police crash reports. From this analysis, the authors were able to identify a common crash scenario involving RTOR. Often, a driver who is stopped prior to turning right focuses on traffic coming from the left in order to identify a gap adequate to permit his right turn. Consequently, the motorist does not see a pedestrian or bicyclist on his right and a conflict occurs when the turn is initiated. The Preusser team found that RTOR accidents account for 1% to 3% of all pedestrian and bicycle accidents (*46*).

Discussion: Restrict Right-Turn-On-Red

A study conducted in Arlington County, VA evaluated the comparative safety benefits of two methods for restricting RTOR movements: traffic signs that limit RTOR during specific time periods vs. highly visible traffic signs that disallow RTOR when pedestrians are present (*43*). The study took place at 15 signalized intersections targeted by the Department of Public Works for implementation of pedestrian safety measures, partly because of public concern over RTOR conflicts. A third of the intersections (5 sites) served as the control group, while the others were equally divided between the two treatments. At the first group of five treated sites, signs were placed that stated “NO TURN ON RED, 7 AM – 7 PM, MON – FRI”. At the second group of five treated sites fluorescent yellow-green reflective signs reading “NO TURN ON RED – WHEN PEDESTRIANS ARE PRESENT” were implemented.

Observations of pedestrian and motorist behavior were conducted at each location during the before and after phases. The researchers found a small but statistically significant increase in the percentage of drivers who actually stopped at painted stop lines prior to turning at the sites with signs related to the presence of pedestrians. Large increases were noted at the intersections where time-specific RTOR restrictions were imposed, whether pedestrians were present or not (*43*).

During the “before” period, 80% of all observed vehicles actually turned right on red at these locations. After installation of the signs, there was a small decline in the percentage of motorists who turned right on red at the sites with signs restricting right turns when pedestrians are present, and a large decrease where RTOR was not permitted during specified time periods (*43*).

Thirty-nine percent of all vehicles observed did not come to a full stop before making a RTOR during the before period. This figure decreased greatly when time-specific signs were installed, but there was little change at locations where pedestrian presence was a factor for drivers to consider (*43*).

In terms of pedestrian behavior, 14% yielded to drivers making a RTOR during the “before” period. After installation of the signs, there was a large decrease in those who yielded to vehicles turning right at time-specific locations, with little change at sites that disallowed RTOR in the presence of pedestrians (*43*).

Overall, the Retting et al. concluded that signs that made RTOR dependent on driver discretion related to the presence or absence of pedestrians were less effective. Signs that prohibit RTOR during daytime hours, when pedestrians are more numerous anyway, might be preferable (*43*).

Another study looked at the safety effects of RTOR in South Carolina and Alabama. In South Carolina, accidents at signalized intersections involving right-turning vehicles for two years before and three years after the RTOR law was implemented were compared with accidents in the same period that did not involve right-turning vehicles. A similar comparison in Alabama covered three years before and five years after RTOR was instituted (*45*).

Results showed a statistically significant increase during the after period in South Carolina for right-turning property damage accidents than for accidents not involving right turns. This was not true in Alabama. There was no statistically significant difference in the rate of change in fatality or injury accidents in either state when comparing right-turning vehicles to non-right-turning vehicles. Furthermore, there was no evidence of increased pedestrian accidents resulting from RTOR in either South Carolina or Alabama (*45*).

Additional discussion of the safety effects of right-turn-on-red is included in Section4.2.2.2.

Summary

There is a wide variety of traffic control measures that have been used and evaluated related to improving pedestrian safety. The presence of special signal timing such as exclusive or "scramble" timing has been shown to reduce pedestrian crash risk by approximately 50% for intersections which have more than 1,200 pedestrians per day, generally found in downtown areas. Such timing requires a longer cycle length thus it needs to be studied in conjunction with increased pedestrian and motorist delay. Although concurrent (or standard) timed pedestrian signals (i.e., where pedestrians get a WALK signal parallel to through traffic, which conflicts with right-turning and left-turning vehicles) showed no significant reduction in pedestrian crashes compared to no pedestrian signals, pedestrian signals are essential for many types of signalized locations (e.g., on one-way streets where pedestrians cannot see the vehicle signals, on wide streets, at complex intersections, or where there is separate left-turn phasing), and can also be important in providing information to pedestrians relative to when it is safe to begin crossing the street. In general, pedestrian signals should be considered for installation at all signalized locations. They are particularly important where pedestrians cannot see the traffic signals, at complex intersections, and where pedestrians cross wide streets. Early release timing and pedestrian countdown signals are also options to enhance pedestrian signals, although the safety effect of these treatments has not been adequately quantified. However, pedestrian countdown signals appear to improve pedestrian crossing behavior and reduce conflicts with motor-vehicles.

Pedestrian-related signing, as described in the MUTCD, is used at intersections. These include regulatory signs ("Yield to Pedestrians in Crosswalks"), warning signs (e.g., advance pedestrian crossing signs), and guide signs (e.g., signs directing pedestrians to walkways, trails, and overpasses). Florescent yellow-green signs are more noticeable by drivers and may result in increased motorist yielding to pedestrians. Allowing right-turn-on-red has shown mixed results, although RTOR crashes involving pedestrians are extremely rare. No turn on red (NTOR) signs may be appropriate at certain locations such as at intersections with poor sight distance, complex intersection design or phasing, and/or high volumes of pedestrians. Such treatments as larger NTOR signs, "red ball" NTOR signs, and electronic NTOR signs (illuminated during the red interval) seem to be more effective than standard NTOR signs in terms of motorist compliance to RTOR regulations, however the safety effect of all these treatments has not been adequately quantified.

There are a variety of innovative signs and signal options that seem promising, based on studies of conflicts and/or pedestrian and motorist behaviors. For example, automated pedestrian detectors at signalized intersections will detect pedestrians waiting to cross the street and give a pedestrian the WALK signal (without having to push the button) and/or extend the clearance interval for a slow-walking pedestrian in the street. Such devices have shown to reduce pedestrian violations and conflicts between pedestrians and motor vehicles. Signs in the street at unsignalized pedestrian crossings (such as "Stop for Pedestrians in Crosswalk) can increase motorist yielding. Again, the safety effect of all these treatments has not been adequately quantified.

4.3.5.2. Bicyclist Traffic Control

According to Hunter et al. (1996), 50% to 70% of all crashes between bicycles and motor vehicles occur at or near intersections. A number of traffic control devices have been developed and tested in the U.S. and abroad to facilitate the safe passage of bicyclists through intersections, as discussed below. Much of the information below related to bicycles was adopted from a summary of literature compiled by Hunter et al. for "A Comparative Analysis of Bicycle Lanes versus Wide Curb Lanes: Final Report" (*91*).

This section provides information on traffic control features to accommodate bicyclists at signalized and unsignalized intersections. Specific treatments discussed include:

- Colored bicycle crossings
- Profiled pavement markings
- Advance stop line (ASL) bike box

Section 3.3 provides discussion of bicycle treatments along roadway segments. Bicyclist design elements at intersections are discussed in Section 4.3.3.

More testing is needed to better quantify the effect on behaviors, conflicts, and crashes of such treatments as colored bike lanes, advance stop lines (bike boxes) at intersections, and profiled or "slalom" lane markings at intersection approaches.

Exhibit 4-96: Resources examined to investigate the safety of bicyclists at intersections

DOCUMENT	DESCRIPTION	COMMENT
NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	On-going project.	Results may be added if relevant when available.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook that summarizes the effects of a wide range of safety measures.	Not added to synthesis
(*111*) (Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Brief summary of past research on a variety of treatments	Added to synthesis

DOCUMENT	DESCRIPTION	COMMENT
(*92*) (Jensen, S. U., "Cyclist Safety at Signalised Junctions." Amsterdam, Netherlands, Velo Mondial 2000, (2000))	Danish study that evaluated the effect of advance bicycle merging treatments on bicyclist crashes at 11 intersections in Denmark	Suggested by NCHRP 17-18(4). Added to synthesis.
(*91*) (Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. F., and Pein, W. E., "A Comparative Analysis of Bicycle Lanes versus Wide Curb Lanes: Final Report." *FHWA-RD-99-034*, McLean, Va., Federal Highway Administration, (1999))	Comparative analysis of bicycle lanes versus wide curb lanes, sites in CA, FL, and TX, used conflicts as surrogate for safety	Suggested by NCHRP 17-18(4). Added to synthesis
(Hunter, W. W., Stewart, J. R., and Stutts, J. C., "A Study of Bicycle Lanes Versus Wide Curb Lanes." Transportation Research Record: Journal of the Transportation Research Board, No. 1667, Washington, D.C., Transportation Research Board, (1999) pp. 70-77.)	Comparative analysis of bicycle lanes versus wide curb lanes, sites in CA, FL, and TX, used conflicts as surrogate for safety	Suggested by NCHRP 17-18(4). Not added to synthesis
(Hunter, W. W., Stewart, J. R., Stutts, J. C., Huang, H. H., and Pein, W. E., "Bicycle Lanes Versus Wide Curb Lanes: Operational and Safety Findings and Countermeasure Recommendations." FHWA-RD-99-035, McLean, Va., Federal Highway Administration, (1999))	Comparative analysis of videotaped behavior of bicyclists and motorists at 16 intersections with either a bike lane or wide curb lane; sites in CA, FL, and TX; also looked at conflicts and lateral positioning of bicyclists	Not added to synthesis
(*93*) (Hunter, W. W., Harkey, D. L., and Stewart, J. R., "Portland's Blue Bike Lanes: Improving Safety through Enhanced Visibility." Portland, Ore., City of Portland, (1999))	Study of colored bike lanes in Portland, Oregon.	Limited qualitative information added to synthesis.
(Brude, U. and Larsson, J., "The Safety of Cyclists at Roundabouts: A Comparison between Swedish, Danish, and Dutch Results." Nordic Road and Transport Research, No. 1, Linköping, Sweden, Johnny Dahlgren Grafisk Produktion AB, (1997) pp. 23-25.)	A summary of safety studies on cyclist safety at roundabouts from Sweden, Denmark, and the Netherlands	This article to be covered under Pedestrian and Bicyclist Safety at Roundabouts. Not added to synthesis.
(Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	Report to Congress	No AMFs. Not added to synthesis.
(Wilkinson, W. C., Clarke, A., Epperson, B., and Knoblauch, R., "The Effects of Bicycle Accommodations on Bicycle/Motor Vehicle Safety and Traffic Operations." FHWA-RD-92-069, Washington, D.C., Federal Highway Administration, (1994))	Conclusions are provided on bicycle planning and design based on the current state of the practice; recommendations are based on a literature review	Used as a reference. Not added to synthesis.
(Zegeer, C. V., Stutts, J. C., and Hunter, W. W., "Safety Effectiveness of Highway Design Features: Volume VI - Pedestrians and Bicyclists." FHWA-RD-91-049, Washington, D.C., Federal Highway Administration, (1992))	Summarizes the safety effectiveness of various geometric features on pedestrian and bicycle safety, based on critical reviews of literature	Used as a reference. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M., "The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents." Journal of Safety Research, Vol. 13, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 45-55.)	Examined the effects of RTOR on pedestrian safety	Not relevant to this section. Not added to synthesis.

Discussion: Colored bicycle crossings

An interesting alternative is the use of color to designate bicycle path crossing points. After the bike crossings at five Montreal intersections were marked with blue pavement, it was found that cyclists obeyed stop signs and stayed on the designated crossing more often. This improved cyclist behavior and, in turn, reduced the level of conflict between bicyclists and drivers (*91*).

In an evaluation of blue bike lanes in Portland, Oregon, in 1999, Hunter, Harkey, and Stewart collected and examined motorist behavior, motorist and cyclist view-points, and conflicts (using videotape) at exit ramps, right-turn lanes, and entrance ramps (*93*). City officials also conducted a field survey of cyclists and a mail survey of motorists. The results showed that after the blue bike lane sections were installed, the following statistically significant results were found (*93*):

- Increase in the proportion of motorists yielding to cyclists
- Increase in the incidence of motorists slowing or stopping when they approach the conflict areas
- Decrease in motorist use of their turn signals
- Decrease in hand signaling and head turning by cyclists
- Increase in the use of the recommended path and a decrease in slowing by cyclists

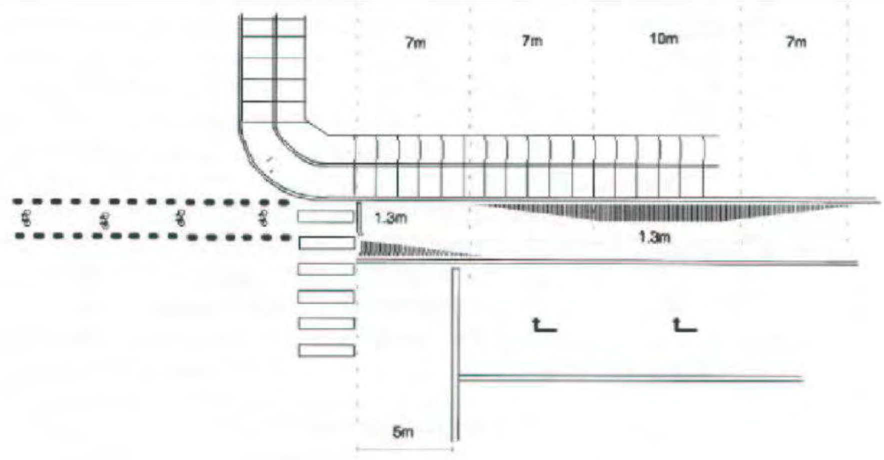
In addition, Hunter et al. found a reduction in conflicts (although sample sizes were small), and an overwhelming majority of cyclists and “close to a majority of motorists” who reported that the addition of the blue bike lanes improved safety (*93*).

As a result of this study, the City of Portland recommended that blue coloring of bike lanes should continue to be installed to improve the visibility of conflict areas involving bicyclists and motor vehicles, and that video monitoring of such sites should continue (*93*).

Discussion: Profiled pavement markings

A 2000 study by Jensen involved evaluating new intersection configurations to better accommodate bicyclists at 11 signalized intersections in 5 municipalities in Denmark (*92*). The intersection pavement marking designs involved installing cycle tracks with narrow bicycle lanes up to the stop lines. “Slalom” bike lanes were used along with staggered stop lines, as well as cycle crossing markings and “profiled stripes”. Exhibit 4-97 illustrates the striping configuration of these treatments. A before-after study of bicycle crashes revealed that bicycle crashes were reduced at 7 out of the 11 intersections where the treatments were tested; three intersections experienced an increase in accidents. There was a 30% reduction in crashes between right-turning motor vehicles and through cyclists. On road sections where there were “entrances and exits” (presumed to be driveways) on the intersection approach where the truncated cycle paths were used, cycle crashes increased significantly.

Exhibit 4-97: Layout of “slalom” bike lane on intersection approach with staggered stop line and marked bike crossing (92)



In a study done in Denmark, profiled pavement markings were evaluated (Herrstedt et al., 1994, as summarized in (*93*)). Such markings are installed on the pavement between bike lanes and motor vehicles lanes to increase the lateral distance between bicyclists and drivers on intersection approaches, and to increase attentiveness on the part of both these types of roadway users. Profiled pavement markings were applied at four-leg and T-intersections (traffic control not reported) to guide approaching bicyclists closer to the regular travel lanes and then divert them away from those lanes at the intersection itself. These profiled markings produced positive changes in both motorist and cyclist behavior. It was found that more drivers adapted their speeds to that of the bicyclists. More motorists stayed behind the stop line at the intersection, and fewer of them made a right turn in front of someone on a bicycle. It was also noted that cyclists became alert sooner at T-intersections with the profiled markings to guide them (*93*). Further details on the study, such as the duration of the study period, were not reported.

Discussion: Advanced stop line (ASL) or bike box

The advanced stop line (ASL) or “bike box” is a pavement marking pattern designed to give priority to bicyclists over motor vehicles, and can increase the visibility between motorists and bicyclists. This treatment can be used at signalized intersections on roads with a marked bike lane. The stop line for motor traffic is applied in advance of the intersection, which creates a clear space, or “box”, where cyclists can wait in front of the cars and then proceed ahead of them into the intersection when the light turns green. This treatment reduces conflicts between bicyclists and turning motor vehicles by making the cyclists easier to see (*93*).

A single signal placed at the bike box can be used to control traffic at these locations. However, in the United Kingdom, a two-signal design is sometimes used. In this system, a red light requires motor vehicles to remain stopped while a special green light directs cyclists ahead to the box (*93*).

In the United Kingdom, bike boxes have proved helpful at intersections with traffic volumes up to 1,000 veh/hr. The safety impact of bike boxes with higher traffic volumes was not found in the literature. Two studies involving nine signalized intersections revealed that two-thirds or more of the bicyclists used the cycle lane and the bike box, while less than 20% disobeyed the signal (Wheeler, 1995 as cited in (*93*)). However, up to 16% of the motorists encroached into the bike lanes, and more than half of the lead drivers at one location violated the advanced stop line in front of the bike box. It was also found that the two-signal system was no more effective than the single signal if the roadway design included a mandatory bike lane and colored pavement in the areas designated for bicycle use (Wheeler, 1995 as cited in (*93*)).

In a review of the Wheeler study, Forbes notes that the study is a “naïve before-after crash study in which … [the] overall number of crashes is too low to draw any statistically significant conclusions” (*111*). Forbes also states that signal phasing was modified at one of the intersections five months prior to the installation of the advance stop line, a traffic signal was added at another site along with the advance stop line. At a third site, a turn prohibition was implemented shortly prior to installation of the advance stop line. Thus, Forbes implies that the changes in crashes may be in part due to these other treatments, and not from the advance stop lines alone (*111*).

Recessed, or advanced, stop lines have also been used in Denmark. In one study, it was determined that recessed (or advanced) stop lines significantly decreased crashes between cyclists passing through the intersection and motorists turning right (Herrstedt et al., 1994 as cited in (*93*)).

In conclusion, it appears that recessed/advanced stop lines increase cyclist safety at intersections, and the bike box may also be beneficial, although an ideal design and quantification of the safety effect are not known at this time.

4.3.6. Weather Issues [Future Edition]

In future editions of the HSM, the safety effect of weather issues on facilities to accommodate bicyclists and pedestrians will be addressed here. This may include the provision of shelters or canopies, and non-slippery surfaces on sidewalks and crosswalks. This section will add to the knowledge presented in other sections on weather issues. Potential resources are listed in Exhibit 4-98.

Exhibit 4-98: Potential resources on weather issues and pedestrian and bicyclist safety at intersections

DOCUMENT
(Ekman, L. and Hyden, C., "Pedestrian Safety in Sweden." FHWA-RD-99-091, McLean, Va., Federal Highway Administration, (1999))
(Jones, T. L. and Tomcheck, P., "Pedestrian Accidents in Marked and Unmarked Crosswalks: A Quantitative Study." ITE Journal, Vol. 70, No. 9, Washington, D.C., Institute of Transportation Engineers, (2000) pp. 42-46.)

4.4. Safety Effects of Other Intersection Elements

Other intersection elements include illumination, access points, signal heads and hardware, transit stops, flashing beacons, strobe-light red signals, weather, and pavement materials. The safety effect of characteristics contained in these elements will be addressed in the following sections. Readers may also wish to review material related to these elements in Section 3.4.

4.4.1. Illumination

Artificial illumination is often provided at intersections in urban and suburban areas, and also at some intersections in rural settings with higher volumes or more complex decisions for drivers.

This section presents evidence regarding the safety effect of public lighting at intersections. This refers to the introduction of lighting at intersections that did not previously have it. Effect will be stated according to accident severity.

For future editions of the HSM there is a need to quantify the safety impacts of the following elements:

- Effect of illumination on the crash risk of the intersection, including risk to pedestrians, cyclists, and other users
- Different types of illumination (i.e., high mast, low light)

Exhibit 4-99: Resources examined to investigate the safety effect of illumination at intersections

DOCUMENT	DESCRIPTION	COMMENT
(*133*) Harkey et al., "Accident Modification Factors for Traffic Engineering and ITS Improvements", *NCHRP Report* 617 (2008), TRB.	An expert panel reviewed several studies and developed an AMF.	Added to synthesis.
(*140*) (Bruneau, J.-F., and Morin, D., "Standard and Nonstandard Roadway Lighting Compared with Darkness at Rural Intersections", *Transportation Research Record* 1918, (2005), pp. 116-122)	Compared the crash rates during day and night at rural intersections with and without lighting.	Not added to synthesis. Other studies (Elvik and Vaa, 2004) used more defensible methods
NCHRP 3-72: Lane Widths, Channelized Right Turns, and Right-Turn Deceleration Lanes in Urban and Suburban Areas http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+3-72	May provide additional insight when complete.	Expected completion May 2005
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	A synthesis of results complied from literature, contact with state and local agencies throughout the United States, and federal programs	No new information. Not added to synthesis.
(Campbell, B. J, Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	A synthesis of research studies on pedestrian safety	No new information. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Accidents Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies aimed at reducing accidents involving older drivers.	No new information. Not added to synthesis.
(*5*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Meta-analysis of many treatments, including illumination. Reanalysis of Wanvik (2004).	Added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Synthesis of a variety of reports on the reduction of accidents at unsignalized intersections	No new information. Not added to synthesis.
(Sullivan, J. M. and Flannagan, M. J., "The Role of Ambient Light Level in Fatal Crashes: Inferences from Daylight Saving Time Transitions." Accident Analysis and Prevention, Vol. 34, No. 4, Oxford, N.Y., Pergamon Press, (2002) pp. 487-498.)	Three specific countermeasures were tested against each other in a single scenario that would be reasonable match to each	Does not address the effects of lighting. Not added to synthesis.
Yi, Ping.; John, L. J.; Dissanayake, S.; and Zang, Y. Impact of highway Illumination on Traffic Fatality in Various Roadway and Environmental Conditions. Transportation Research Record, TRB, National Research Council, Washington, D.C., 2002	This study compares collisions in lighted and unlighted conditions by evaluating the interaction of roadway, traffic, weather conditions and age of driver at the time of collisions. The two-way ANOVA technique was used to evaluate the interactions.	No safety effects reported. Not added to synthesis.
(Jones, T. L. and Tomcheck, P., "Pedestrian Accidents in Marked and Unmarked Crosswalks: A Quantitative Study." ITE Journal, Vol. 70, No. 9, Washington, D.C., Institute of Transportation Engineers, (2000) pp. 42-46.)	A research study including the review of current practice and before and after studies	Not relevant to this section. Not added to synthesis.
(*114*) (Preston, H. and Schoenecker, T., "Safety Impacts of Street Lighting at Rural Intersections." 1999, St. Paul, Minnesota Department of Transportation, (1999))	Conducted both a cross-sectional study (3,400 intersections) and a before-and-after analysis (12 intersections) of the effect of street lighting on rural intersection safety	Suggested by 17-18(4). Added to synthesis.
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))	A synthesis of a relationships between measures of raod performance and road asset features, primarily based on literature review and investigation	No AMFs. Not added to synthesis.
(*112*) (Elvik, R., "Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure." Transportation Research Record 1485, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 112-123.)	Meta-analysis of 37 studies on the safety effect of illumination; illumination of various types of roadway segments included	Suggested by 17-18(4). Added to synthesis.
(Compton, R. P. and Milton, E. V., "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration." DOT HS 808, Washington, D.C., National Highway Traffic Safety Administration, (1994))	A report based on data from current operations, a literature review of previous research, and results of analysis on current data	No relevant information. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Keck, M. E., "The Relationship of Fixed and Vehicular Lighting to Accidents." FHWA-SA-91-019, McLean, Va., Federal Highway Administration, (1991))	Synthesis of lighting research from 1979 to 1988	Suggested by 17-18(4). Refers to Richards (1981) included in Elvik (1995). Not added to synthesis.
(Anderson, K. A., Hoppe, W. J., McCoy, P. T., and Price, R. E., "Cost-Effectiveness Evaluation of Rural Intersections Levels of Illumination." Transportation Research Record 996, Washington, D.C., Transportation Research Board, National Research Council, (1984) pp. 44-47.)	Analyzed the effect on conflicts of various levels of illumination at one rural intersection	Suggested by 17-18(4). Did not employ accident data. Not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	A synthesis of safety research categorized into 17 subjects and presented as individual chapters.	Included in Elvik (1995). Not added to synthesis.
(Lipinski, M. E. and Wortman, R. H., "Effect of Illumination on Rural At-Grade Intersection Accidents." Transportation Research Record 611, Washington, D.C., Transportation Research Board, National Research Council, (1978) pp. 25-27.)	Cross-sectional study, 445 rural intersections in IL	Suggested by 17-18(4). Included in Elvik (1995). Not added to synthesis.

A meta-analysis of 37 evaluation studies containing 142 estimates of effect has been reported by Elvik (1995) (*112*). This analysis serves as the main source of evidence used in this section. The analysis has been updated by adding the studies of Griffith (1994) (*113*), Preston (1999) (*114*) and Wanvik (2004), the latter subject to a re-analysis by Elvik (2004) (*5*). This brings the total number of studies to 40 and the total number of estimates of effect to 152. State-of-the-art techniques of meta-analysis have been applied to summarize evidence from these studies.

Results of studies that deal specifically with illumination in intersections have been selected. There are 32 estimates of effect that refer to intersections and 18 estimates of effect that refer to pedestrian accidents. Pedestrian accidents have been included because they often occur at, or close to, intersections.

Studies have been classified in three groups according to study quality. Studies rated as high quality include studies using both an internal and external comparison group (the distinction between external and internal comparison is explained below) and matched case-control studies. Studies rated as medium quality include studies that provide data on traffic volume in addition to accident data, and studies using an external comparison group only. Studies rated as low quality include studies that use only an internal comparison group and simple (as opposed to matched) case-control studies. Most studies, representing 74% of the estimates of effect, have been rated as low quality. Standards errors have been adjusted by a factor of 1.2 in high quality studies (all study designs), 2 in medium quality before-and-after studies, and 3 in low quality before-and-after studies. In case-control or cross-section studies, standard errors were adjusted by a factor of 3 medium quality studies and a factor of 5 in low quality studies.

An internal comparison group refers to the use of daytime accidents as comparison group when estimating the effect on lighting. As an example, suppose there were 80 accidents in daytime and 55 in darkness at an intersection before lighting was installed. Further, suppose the number of accidents in daytime increased to 84 and the number of accidents in darkness declined to 39 after lighting was installed. The effect would then be estimated to: (39/55)/(84/80) = 0.675.

This study design does not control for two potential confounding factors: (1) Long-term trends in the proportion of accidents occurring in darkness, and (2) Regression-to-the-mean, in particular with respect to an abnormally high proportion of accidents in darkness. To some extent, both these confounding factors can be controlled for by using an external comparison group, i.e. intersections where lighting has not been installed. Suppose, for example, that for comparison intersections where lighting was not installed, the following numbers were observed during before and after periods matching the location above where lighting was installed: daytime before = 112; daytime after = 119; darkness before = 58; darkness after = 54. Then, in the comparison group, the odds ratio would be: (54/58)/(119/112) = 0.876. The adjusted estimate of effect (ratio of odds ratios) would be: 0.675/0.876 = 0.771.

Exhibit 4-100 shows summary estimates of the effects of lighting on accidents. Effects are stated as odds ratios. Uncertainty in summary estimates of effect is stated as adjusted standard error. All estimates of effect refer to accidents in darkness only.

Three sets of summary estimates of effect are presented in Exhibit 4-100. The first is based on conventional meta-analysis. The second set has been generated from coefficients estimated in meta-regression analysis. In theory, the meta-regression estimates are superior to the conventional summary estimates, since they control for more confounding factors or imbalance in the distribution of estimates across moderator variables (a moderator variable is any variable that influences the size of the effect of a measure on accidents) (*5*). The third set is based on an expert panel that was assembled as part of NCHRP Project 17-25 (*133*) that reviewed the work by Elvik and Vaa (*5*) and also used additional information on the distribution of crashes by injury severity and time of day from North Carolina and Minnesota.

Only estimates that specify accident severity have been used. Estimates referring to “all” accidents, which is usually a mixture of injury accidents and property-damage-only accidents have been discarded. The number of estimates underlying each summary estimate is stated in parentheses.

No study estimating the effect on intersection illumination on fatal accidents has been found. Both injury accidents and property-damage-only accidents appear to be reduced. The effect attributed to illumination is larger according to the meta-regression analysis than it is for the conventional meta-analysis.

Pedestrian accidents are strongly reduced when illumination is provided. Again, the meta-regression summary estimates of effect indicate somewhat larger effects than the conventional meta-analysis summary estimates do. The reasons for this are not clear. It is fairly common in road safety evaluation research to find that more well-controlled studies attribute a smaller effect to the measure evaluated than less well-controlled studies. In this case, the meta-regression approach must be considered as a more well-controlled approach than the conventional approach to meta-analysis. It is therefore a bit surprising that the effects attributed to road lighting are larger in the meta-regression approach than in the conventional approach.

Exhibit 4-100: Summary estimates of the effects on accidents of lighting in intersections (5)

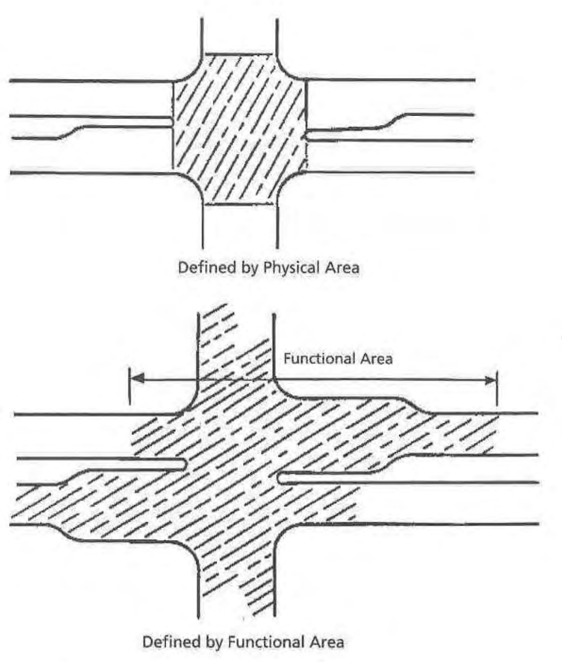
Author, date	Treatment/ Element	Setting	Intersection Type & Volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Summary estimates based on conventional meta-analysis						
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime Fatal	No study	No study
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime Injury (16)	0.624	0.126
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime PDO (16)	0.688	0.361
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	Pedestrian Nighttime Fatal	0.216	0.865
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	Pedestrian Nighttime Injury	0.576	0.176
Summary estimates based on meta-regression analysis						
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime Fatal	0.228	0.282
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime Injury (16)	0.504	0.205
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	All types Nighttime PDO (16)	0.515	0.214
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	Pedestrian Nighttime Fatal	0.185	0.281
Elvik and Vaa, 2004	Lighting in intersections	Unspecified	All settings All types	Pedestrian Nighttime Injury	0.409	0.203
Estimates based on expert panel review of Elvik and Vaa, 2004, and crash statistics						
Harkey et al. (2008)	Lighting in intersections	Unspecificed	All settings All types	Nighttime crashes; all types; all severities	0.790	n/a
Harkey et al. (2008)	Lighting in intersections	Unspecificed	All settings All types	Nighttime crashes; all types; injury and fatal	0.710	n/a

4.4.2. Other Access Points within the Functional Area

The management of access, namely the location, spacing, and design of private and public intersections, has been identified as one of the most critical elements in roadway planning and design. Access management provides or manages access to land development while simultaneously preserving traffic safety, capacity, and speed on the surrounding road system, thus addressing congestion, capacity loss, and accidents on the nation's roadways (*115*). In particular, the number of access points, coupled with the speed differential between vehicles traveling along the roadway, contributes to rear-end crashes (*4*).

Driveways are, in effect, at-grade intersections and should be designed consistent with the intended use. It has been noted that the number of accidents is disproportionately higher at driveways than at other intersections; thus their design and location warrant special consideration (*115*). With regards to the proximity of driveways to intersections, the AASHTO Green Book specifically states that "driveways should not be situated within the functional boundary of at-grade intersections" (*116*). The concept of the functional area for an intersection is illustrated in Exhibit 4-101. While AASHTO does not present guidelines as to the size of the functional area of an intersection, it has been suggested that the functional boundary include all required storage lengths for exclusive turn lanes and for through traffic, plus any maneuvering distance for the exclusive turn lanes.

Exhibit 4-101: Function and physical area of an intersection (115)



ITE identified a number of factors for consideration when designing access to developments (*115*). These include (1) limiting the number of access points, (2) separating conflict areas, (3) reducing acceleration and deceleration requirements at access points, (4) removing turning vehicles from through-travel lanes, (5) spacing major intersections to facilitate progressive travel speeds along arteries, and (6) providing adequate on-site storage at major development access locations. The main focus of this subsection is on the control of access points within the functional area of intersections. The other access design factors are addressed in the other sections of the HSM, as identified below.

Additional information is available in the Access Management Manual produced by the Transportation Research Board Committee on Access Management (ADA70) (http://www.accessmanagement.gov/manual.htm), as well as the Access Management CD Library developed by the Florida DOT (http://www.dot.state.fl.us/planning/systems/sm/accman).

This section discusses the safety effects of access points within the functional areas of at-grade intersections for all road classes.

Given that safety impacts of access management at intersections is closely related to the separate design and traffic control components that constitute those intersections, the reader may wish to review Sections 4.1 and 4.2 for additional information on approach roadway elements and intersection traffic control, respectively. Chapter 7 contains further discussion on the safety effect of access management principles.

Exhibit 4-102: Resources examined to investigate the safety effect of Access Points at Intersections

DOCUMENT	DESCRIPTION	COMMENT
(*18*) NCHRP Project 17-26 "Methodology to Predict the Safety Performance of Urban and Suburban Arterials" http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+17-26	Interim report for study designed to develop a methodology to predict the safety performance of various elements such as Lane width, Shoulder width and curbs, etc. on urban and suburban arterials.	Added to synthesis. Only discussion on safety impact of driveways located close to intersections have been added to synthesis. No quantitative evidence of safety impacts found because reference is only a draft interim report—the research is still ongoing.
(*4*) (Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Report provides guidance on strategies designed to improve safety at signalized intersections and especially to reduce fatalities. Only presents results from select previous research studies.	Added to synthesis. Only anecdotal evidence and discussion on potential safety effect of restricting access close to intersections provided and added to synthesis.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Not added to synthesis. Information found in Chapter 3.5 of reference is related to access on roadway segments, not intersections.
(*10*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Harwood, D. W., Potts, I. B., Torbic, D. J., and Rabbani, E. R., "NCHRP Report 500 Volume 5: A Guide for Addressing Unsignalized Intersection Accidents." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Report is a detailed implementation guide that provides guidance and strategies to improve safety at unsignalized intersections.	Added to synthesis. Only anecdotal evidence and discussion on potential safety effect of restricting access close to intersections provided and added to synthesis.
(*118*) (Hauer, E., "Access and Safety." (2001))	Reference is a critical review of studies that investigated the safety effects of intersection spacing and driveway density.	Not added to synthesis. Focus of study is the safety effect of access management elements on roadway segments, not intersections.

DOCUMENT	DESCRIPTION	COMMENT
(Xu, L., "Right Turns Followed by U-Turns Versus Direct Left Turns: A Comparison of Safety Issues." ITE Journal, Vol. 71, No. 11, Washington, D.C., Institute of Transportation Engineers, (2001) pp. 36-43.)	Cross-sectional study comparing accident rates and accident frequencies between direct left turns and an alternative left-turn design (i.e. right-turn, followed by U-turn)	Not added to synthesis. Treatment being examined is the type of left-turn configuration and not directly related to the number of access points in close proximity to the intersection. Reference is more relevant intersection types and alternative left-turn treatments.
(Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	Study presents an algorithm for predicting the safety performance of various factors for roadway segments and for at-grade intersections on rural two-lane highways	Not added to synthesis. Although base models developed by researchers for four-leg stop and signal controlled intersections take into consideration the number of driveways in the vicinity of intersections, it is based on a small data set and cannot be used to derive AMFs.
(*39*) Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999)	Discusses methods for predicting and analyzing safety and traffic operational effects of selected access management techniques.	Added to synthesis.
(Vogt, A., "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized." FHWA-RD-99-128, McLean, Va., Federal Highway Administration, (1999))	Analyzed the relationship between crashes and intersection elements at 3 types of rural intersections in CA and MI	Not added to synthesis. Base models developed by researchers for four-leg stop and signal controlled intersections were already incorporated into a more recent study by Harwood et al. (2000) and reviewed previously.
(*117*) (Lall, B. K., Eghtedari, A., Simons, T., Taylor, P., and Reynolds, T., "Analysis of Traffic Accidents within the Functional Area of Intersections and Driveways." TRANS-1-95, Portland, Ore., Portland State University, Department of Civil Engineering, (1995))	Cross-section study comparing accident frequencies at urban and rural isolated intersections and influenced intersections.	Added to synthesis. t and s values calculated using reported crash data.
(McGuirk, W. W. and Satterly, G. T., "Evaluation of Factors Influencing Driveway Accidents." Transportation Research Record 601, Washington, D.C., Transportation Research Board, National Research Council, (1976) pp. 66-72.)	Study investigated the factors that influence driveway accidents through the development of various regression equations.	Suggested by 17-18(4). Not added to synthesis. Insufficient data to determine t and s values. Regression equations relating accidents to the spacing between driveways and adjacent intersections were deemed to be invalid by the authors themselves following results from statistical analysis.
(Box, P. C., "Driveways." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 5, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Chapter discusses the relationship between accidents and driveways / access management	Not added to synthesis. Insufficient data to determine t and s values. Material not relevant to HSM.

The effectiveness of closing or relocating driveways outside of the functional areas of intersections has been quantified for two-lane and multi-lane rural highways, and urban and suburban arterials. Traffic volume ranges and other pertinent information are provided when available. Although the safety impact of restricting turn movements at driveways located in close proximity to intersections has not been quantified, a brief discussion on this particular treatment is also included here.

Treatment: Closure or Complete Relocation of Driveways near Intersections

Lall et al. conducted a cross-section study that compared the accident frequencies at isolated intersections against those at influenced intersections, in both urban and rural areas (*117*). The intersections examined were classified as either isolated or influenced depending on the presence of driveways within the functional area of the intersection being studied. Intersections investigated in the study were unsignalized and matched in terms of the traffic volumes, type of traffic control, and posted speed limits. The authors mentioned that for the urban intersections, the traffic volume was 24,000 veh/day for the isolated intersection, and 15,000 veh/day for the influenced intersections; for the rural intersections, the traffic volume was 11,000 veh/day for both influenced and isolated sites (*117*).

Although traffic volume information for intersections is typically expressed in terms of total entering vehicles, for reasons unknown, the traffic volume measure of choice in this study was average daily traffic (ADT); it is unclear from the report if the ADT values were averaged for all approaches to the respective intersections.

Posted speed limits for the urban intersections were 35 and 30 mph for isolated and influenced intersections respectively, while the posted speed limits were 50 mph for all rural sites (*117*). The results from the study are summarized in Exhibit 4-103. A method correction factor of 5 was applied to the s ideal which was calculated based on the number of crashes for influenced intersections and the ratio of exposures (in this case, traffic volume). Note that the AMF values and the corresponding standard errors are large due to the small sample size for crash data used in the study. In addition, it is unclear from the study if the isolated and influenced sites were matched to adequately account for other potential confounding factors such as the type of land use, whether highways were divided or not, etc. There is also the potential for accident migration or spillover, especially since for isolated intersections traffic will have to access abutting land developments via alternative driveways or intersections.

Exhibit 4-103: Safety Effectiveness of Driveway Closure at Intersections (117)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lall et al., 1995	Closure or complete relocation of all driveways from functional area of intersection	Urban	Mix of two- and four-lane divided or undivided highways, ADT = 15,000 to 24,000 veh/day	Total Intersection -Accidents, all severities	0.93	2.31
Lall et al., 1995	Closure or complete relocation of all driveways from functional area of intersection	Urban	Mix of two- and four-lane divided or undivided highways, ADT = 15,000 to 24,000 veh/day	Intersection accidents, Injury	1.67	5.05

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Lall et al., 1995	Closure or complete relocation of all driveways from functional area of intersection	Rural	Mix of two- and four-lane divided or undivided highways, ADT = 11,000 veh/day	Total Intersection -Accidents, all severities	1.17	3.25
Lall et al., 1995	Closure or complete relocation of all driveways from functional area of intersection	Rural	Mix of two- and four-lane divided or undivided highways, ADT = 11,000 veh/day	Intersection accidents, Injury	1.41	4.48

Lall et al. suggested that the greater frequency of accidents at isolated intersections can be attributed to driver expectation. The authors added that for both urban and rural isolated intersections, drivers' lack of expectancy of a conflicting vehicle movement when they are driving on an open corridor can result in accidents when they suddenly encounter a vehicle maneuvering a conflicting path against their own vehicle trajectory. On the other hand, when driving in an area with more intersections and driveways, drivers expect such maneuvers and hence, are more cautious about potential accidents.

It is intuitive and generally accepted that reducing the number of access points within the functional areas of intersections is expected to improve safety (as expressed by Antonucci et al. (*4*) and Neuman et al. (*10*)). It appears that the findings of Lall et al. are counterintuitive and contrary to the conventional belief; each scenario in Exhibit 4-103 is associated with an increase in accidents (AMF>1.0). Further, Antonucci et al. indicate that restricting access to commercial properties near intersections by closing driveways on major roads or moving them to a minor road approach will help reduce conflicts between through and turning traffic, and this, in turn, may lead reductions in rear-end and angle crashes related to vehicles turning into and out of driveways and speed changes near the intersection and the driveway (*4*). In addition to the potential reduction in conflicts, it has been suggested that locating driveways away from intersections also provides more time and space for vehicles to turn or merge safely across lanes (*18*). Neuman et al., add that access points within 250 feet upstream and downstream of an intersection are generally undesirable (*10*).

Discussion: Imposing Turn Restrictions

When a driveway on a high-volume street adjacent to an unsignalized intersection cannot be closed or relocated, it may be appropriate to restrict turning maneuvers at the driveway. For example, left turns at the driveway can be restricted and driveway movements limited to right turns in and right turns out (*10*). By doing so, the number of potential conflict points is reduced, hence reducing the potential for accidents related to vehicles exiting or entering via that driveway. However, the potential for accident migration or spillover to adjacent driveways or intersections must be taken into account. No quantitative estimates of the safety effectiveness of this treatment are currently available.

Discussion: Control of signalized intersection spacing

According to Gluck et al., the spacing of traffic signals, in terms of their frequency and uniformity, governs the performance of urban and suburban highways (*39*). Gluck et al. added that spacing of traffic signals is one of the most important access management techniques and one that is commonly used in States such as Colorado, Florida and New Jersey. For instance, highway agencies in all three states require long signal spacing (e.g., ½ mi) or minimum through band widths (e.g., 50%) along principal arterial roads. Gluck et al. pointed out that several studies conducted in those States have reported that accident rates (per million vehicle miles of travel [MVMT]) generally rise as traffic signal density increases (*39*).

As an example, an increase from two to four traffic signals per mile resulted in roughly a 40% increase in accidents along highways in Georgia and roughly a 150% increase along US 41 in Lee County, Florida. However, the safety effects may be obscured in part by differing traffic volumes on intersecting roadways and by the use of MVMT for computing rates, rather than computing accidents per million entering vehicles. The difficulties that arise from comparisons using MVMT are intrinsic to the way MVMT estimates are calculated. As Hauer pointed out, by adding an intersection one adds accidents but since intersections do not add MVMT, dividing more accidents by the same MVMT is bound to increase the ratio of accidents per MVMT (*118*).

4.4.3. Signal Heads and Hardware [Future Edition]

In future editions of the HSM, this section may include discussion of signal visibility and/or conspicuity, increasing signal head size, providing additional signal heads, installing backplates, lens size, and replacing pedestal mounted signals with mast arm mounted signals. Potential resources are listed in Exhibit 4-104.

Exhibit 4-104: Potential resources on the relationship between signal heads and hardware at intersections and safety

DOCUMENT
(*133*) Harkey et al., "Accident Modification Factors for Traffic Engineering and ITS Improvements", *NCHRP Report* 617 (2008), TRB.
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Accidents at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Bonneson, J.A. and Son, H.J., "Prediction of expected red-light-running frequency at urban intersections", *Transportation Research Record* 1830, pp. 30-47 (2003))
(Thomas, G. B. and Smith, D. J., "Effectiveness of Roadway Safety Improvements." Ames, Iowa Department of Transportation, (2001))
(Sayed, T., Abdelwahab, W., and Nepomuceno, J., "Safety evaluation of alternative signal head design", *Transportation Research Record* 1635, pp. 140-146 (1998))
(Hamilton Associates, "The safety benefits of additional primary signal heads", Insurance Corporation of British Columbia, (1998))
(Gibby, A. R., Washington, S. P., and Ferrara, T. C., "Evaluation of High-Speed Isolated Signalized Intersections in California." Transportation Research Record 1376, Washington, D.C., Transportation Research Board, National Research Council, (1992) pp. 45-56.)
(Bhesania, R. R., "Impact of Mast-Mounted Signal Heads on Accident Reduction." ITE Journal, Vol. 61, No. 10, Washington, D.C., Institute of Transportation Engineers, (1991) pp. 25-29.)

DOCUMENT
(Short, M. S., Woelfl, G. A., and Chang, C. J., "Effects of Traffic Signal Installation On Accidents." Accident Analysis and Prevention, Vol. 14, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 135-145.)

In future editions of the HSM, this section may also discuss the safety impact of using a strobe light in the red signal at an intersection. Strobe lights are used as a supplement to the red lens to draw the attention of drivers to a traffic signal. Potential resources are listed in Exhibit 4-105.

Exhibit 4-105: Potential resources on the relationship between strobe light in the red signal at intersections and safety

DOCUMENT
(Cottrel, B.H. Jr., "Evaluation of the use of strobe lights in the red lens of traffic signals" VTRC 95-TAR-5, Charlottesville, Virginia, Virginia Transportation Research Council, (1994))

4.4.4. Transit Stop Placement [Future Edition]

As defined in the Highway Capacity Manual (*11*), a far-side stop is a transit stop that requires transit units to cross an intersection prior to stopping to serve passengers. The opposite, a near-side stop, is a transit stop prior to the intersection.

In future editions of the HSM, this section may address the safety impact of the positioning and location of intersection transit stops, the impact on pedestrian desire lines, as well as bicycle considerations, mode/transit transfer needs. Potential resources are listed in Exhibit 4-106.

Exhibit 4-106: Potential resources on the relationship between transit stops at intersections and safety

DOCUMENT
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

4.4.5. Flashing Beacons at Unsignalized Intersections

Installing flashing beacons over the intersection or along the roadside can help alert drivers to the presence of unsignalized intersections that may be unexpected or may not be visible. Flashing beacons may be particularly appropriate for intersections with patterns of angel collisions related to lack of driver awareness of the intersection (*10*). Resources reviewed for this treatment are listed in Exhibit 4-107.

Exhibit 4-107: Potential resources on the relationship between flashing beacons at unsignalized intersections and safety

DOCUMENT	DESCRIPTION	COMMENT
(*141*) (Srinivasan, R., Carter, D., Persaud, B., Eccles, K., and Lyon, C., "Safety Evaluation of Flashing Beacons at Stop Controlled Intersections", Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.)	An emprirical Bayes method was used to examine the safety impacts of installing flashing beacons at approaches to stop controlled intersections based on data from North and South Carolina.	Added to synthesis.
(*142*) (Murphy, B.G., and Hummer, J.E., "Development of crash reduction factors for overhead flashing beacons at rural intersections in North Carolina", Presented at the 2007 Annual Meeting of the Transportation Research Board, Washington, D.C., 2007)	Used three different methods including the empirical Bayes method to evaluate the safety impacts of overhead flashing beacons in North Carolina.	Added to synthesis.
(*143*) (Pant, P.D., Park, Y., Neti, S.V., and Hossain, A.B., "Comparative study of rural stop controlled and beacon-controlled intersections", Transportation Research Record 1692, pp. 164-172, 1999.)	Compared the crash rates at six stop controlled intersections without a beacon compared to seven stop-controlled intersections with a beacon.	Added to synthesis.
(*144*) (Cribbins, P.D. and Walton, C.M., "Traffic signals and overhead flashers at rural intersections: their effectiveness in reducing accidents", Highway Research Record 325, pp. 1-4, 1970.)	Evaluated the safety impacts of flashing beacons at rural intersections in North Carolina that were installed after 1965. This study compared the equivalent property damage only (EPDO) rate before the installation of beacons with the EPDO rate after installation.	Added to synthesis.

Cribbins and Walton (*144*) evaluated the safety impacts of flashing beacons at 14 rural intersections in North Carolina that were installed after 1965. Based on the severity level of each accident and the total entering vehicles at the intersections, an equivalent property damage only (EPDO) rate was computed before and after the installation of beacons. Following the installation of the beacons, the EPDO rate decreased by 48 percent. Based on a paired t-test, the authors concluded that the reduction was statistically significant at the 0.01 level.

Pant et al. (*143*) compared the crash rates at six stop-controlled intersections without a beacon compared to seven stop-controlled intersections with a beacon. Fatal, injury, property damage only (PDO), and right-angle crashes were included in the analysis. The mean rates for most accident types were higher at beacon-controlled intersections. A before-after analysis found statistically insignificant reductions in fatal, serious visible injury, and angle accidents following the installation of beacons at 7 sites.

More recently, Murphy and Hummer evaluated the safety impacts of flashing beacons at 34 four-leg two-way stop-controlled locations in North Carolina *(142)*. Three different methods were used to conduct the analysis: naïve before and after analysis, before and after analysis using a safety performance function, and the empirical Bayes (EB) method. The naïve before and after analysis revealed a 10 percent reduction in total crashes, 15 percent reduction in injury crashes, 66 percent reduction in severe injury crashes, 11 percent reduction in frontal impact crashes, and a 50 percent reduction in failure-to-stop crashes. A safety performance function developed by Vogt and Bared *(?)* for intersections in Minnesota was recalibrated using data from 170 reference intersections in North Carolina. This method showed a 13 percent increase in total crashes following the introduction of flashing beacons. The EB approach was applied to account for potential effects of regression-to-the-mean. The EB approach also made use of data from the reference population, but accounted for the increase in traffic volume using a linear assumption. However, considering that the safety performance function used by the authors showed that the relationship between crash frequency and major and minor average annual daily traffic (AADT) is not linear, assuming a linear change will give an incorrect result. Their EB approach revealed a 12 percent decrease in total crashes, 9 percent decrease in injury crashes, 40 percent decrease in severe injury crashes, 9 percent decrease in frontal impact crashes, and 26 percent reduction in failure-to-stop crashes.

Srinivasan et al. (*141*) supplemented the database used by Murphy and Hummer (?) with more sites from North Carolina and also included data from sites in South Carolina. An empirical Bayes analysis was conducted by developing safety performance functions using data on reference groups from North and South Carolina. The results from this study are shown in Exhibit 4-111. This study was rated High and an MCF of 1.2 was applied to the standard errors. Overall, the flashing beacons seem to be effective in reducing crashes, especially right angle crashes. The beacons were more effective in rural and suburban areas compared to urban areas. Results from this study are recommended for the HSM.

Exhibit 4-108: Safety Effectiveness of Flashing Beacons at Four-Leg Stop Controlled Intersections (141)

<table>
<tr><th>Author, date</th><th>Treatment/ Element</th><th>Setting</th><th>Road type & volume</th><th>Accident type & severity</th><th>Index of Effectiveness, $t_{adjusted}$</th><th>Estimate of Std. Error, s</th></tr>
<tr><td rowspan="9">Srinivasan et al., 2008</td><td rowspan="9">Flashing beacons at four leg stop controlled intersections on two lane roads
Standard and actuated beacons</td><td rowspan="4">Rural, Urban, and Suburban;
Two way and four way stop controlled</td><td rowspan="9">Major road volume: 250 to 42,520 vpd
Minor road volume: 90 to 13,270 vpd</td><td>All types
All severities</td><td>0.949</td><td>0.043</td></tr>
<tr><td>All types
Injury</td><td>0.898</td><td>0.0576</td></tr>
<tr><td>Rear end
All severities</td><td>0.921</td><td>0.107</td></tr>
<tr><td>Angle</td><td>0.867</td><td>0.055</td></tr>
<tr><td>Rural</td><td>Angle</td><td>0.843</td><td>0.064</td></tr>
<tr><td>Suburban</td><td>Angle</td><td>0.882</td><td>0.122</td></tr>
<tr><td>Urban</td><td>Angle</td><td>1.123</td><td>0.281</td></tr>
<tr><td>Two-way stop controlled</td><td>Angle</td><td>0.873</td><td>0.056</td></tr>
<tr><td>Four-way stop controlled</td><td>Angle</td><td>0.722</td><td>0.246</td></tr>
</table>

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
	Standard overhead beacons	Rural, Urban, and Suburban; Two way and four way stop controlled		Angle	0.881	0.065
	Standard stop mounted			Angle	0.418	0.196
	Standard overhead and stop mounted			Angle	0.867	0.062
	Actuated beacons			Angle	0.860	0.118

4.4.6. Weather [Future Edition]

In future editions of the HSM, this section may discuss elements of weather similar to the information presented in Section 3.4.4. This section would contain information specific to intersections. The outline of this section is similar to Section 3.4.4: adverse weather and low visibility warning systems; snow, slush and ice control, and wet pavement. No potential resources have been identified for this section.

4.4.6.1. Adverse Weather and Low Visibility Warning Systems [Future Edition]

Some transportation agencies employ advanced highway weather information systems that warn drivers of the occurrence of adverse weather, including icy conditions, or low visibility. These systems may include on-road systems such as flashing lights, changeable message signs, static signs (e.g., “snow belt area”, “heavy fog area”), or in vehicle information systems.

In future editions of the HSM, this section may discuss the safety effect of these weather information systems at intersections. No potential resources have been identified for this section.

4.4.6.2. Snow, Slush, and Ice Control [Future Edition]

It is generally accepted that the presence of snow, slush or ice on the road surface increases the accident rate. A number of measures are used to control snow, slush and ice. In future editions of the HSM, this section may review the effects of these measures on road safety at intersections. No potential resources have been identified for this section.

4.4.6.3. Wet Pavement [Future Edition]

In future editions of the HSM, this section may discuss the safety effect of drainage characteristics, hydroplaning remediation, high-friction pavements (e.g., at specific curve location), and other elements related to wet pavement at intersections. A potential resource is listed in Exhibit 4-107.

Exhibit 4-109: Potential resource on the relationship between increased pavement friction on intersection approaches and safety

DOCUMENT
Harkey et al., "Accident Modification Factors for Traffic Engineering and ITS Improvements", *NCHRP Report* 617 (2008-in press), TRB.

4.4.6.4. Pavement Materials [Future Edition]

In future editions of the HSM, this section may include discussion of the safety impact of pavement surface deterioration, changes to the coefficient of surface friction, and surface rehabilitation, for different surface materials (e.g., asphalt concrete, Portland cement concrete, gravel, tar & gravel, dirt, interlock bricks, grooved pavement, textured roads, etc.) at intersections. No potential resources have been identified for this section.

References

1. Box, P. C., "Intersections." Chapter 4, Traffic Control and Roadway Elements - Their Relationship to Highway Safety, Revised, Washington, D.C., Highway Users Federation for Safety and Mobility (1970).
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137. Shin, K. and Washington, S., "The Impact of Red Light Cameras on Safety in Arizona", *Accident Analysis and Prevention*, 39, (2007), pp. 1212-1221.

138. Sayed, T. and de Leur, P., "Evaluation of Intersection Safety Camera Program in Edmonton, Canada", *Transportation Research Record* 2009, (2007), pp. 37-45.

139. Miller, J.S., Khandelwal, R., and Garber, N.J., "Safety Impacts of Photo-Red Enforcement at Suburban Signalized Intersections: An Empirical Bayes Approach", Transportation Research Record 1969, (2006), pp. 27-34.

140. Bruneau, J.-F., and Morin, D., "Standard and Nonstandard Roadway Lighting Compared with Darkness at Rural Intersections", *Transportation Research Record* 1918, (2005), pp. 116-122.

141. Srinivasan, R., Carter, D., Persaud, B., Eccles, K., and Lyon, C., "Safety Evaluation of Flashing Beacons at Stop Controlled Intersections", Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

142. Murphy, B.G., and Hummer, J.E., "Development of crash reduction factors for overhead flashing beacons at rural intersections in North Carolina", Presented at the 2007 Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.

143. Pant, P.D., Park, Y., Neti, S.V., and Hossain, A.B., "Comparative study of rural stop controlled and beacon-controlled intersections", Transportation Research Record 1692, pp. 164-172, 1999.

144. Cribbins, P.D. and Walton, C.M., "Traffic signals and overhead flashers at rural intersections: their effectiveness in reducing accidents", Highway Research Record 325, pp. 1-4, 1970.

145. Liu, P., Lu, J., and Chen, H., Understanding factors affecting safety of right-turns followed by U-turns, Presented at the 2008 Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

Chapter 5: Interchanges

Chapter 5. Interchanges

CONTENTS

EXHIBITS

EQUATIONS

5.1. Safety Effects of Interchange Design Elements

Interchange types range from cloverleaf to single point designs. Interchanges are comprised of a number of different elements such as: deceleration and acceleration lanes, on-off ramps, ramp terminals, freeway sections between ramps, freeway segments leading to the deceleration lane/off-ramp combination, and the freeway segments adjacent and beyond the on-ramp/acceleration lane combination.

The following sections explore the safety effects of various interchange design elements including interchange type, merge/diverge areas, ramp roadways, and ramp terminals.

This edition of the HSM does not include interchanges along urban expressways, which would benefit from separate consideration due to the distinct land use, urban traffic distribution and characteristics, and travel speeds (as part of urban and suburban arterials).

5.1.1. Interchange Type/Configuration

There are several types of interchanges, including diamond, cloverleaf, single point, partial cloverleaf, directional, and trumpet interchanges. AASHTO's Policy on Geometric Design contains details on interchange types and their characteristics (*1*).

Some interchange types are more appropriate to different applications (e.g., rural versus urban); therefore, the safety effect of various interchange types in various applications will be included in this section where possible.

There may be safety implications on the crossing road for an overpass versus an underpass design condition. The configuration of ramps and the consistency of design along a corridor (e.g., all exit ramps are found in the right side) may have key safety implications when considering driver expectation, as noted in AASHTO's Policy on Geometric Design (*1*). Information on these topics may be included here when available.

This section covers current knowledge related to interchange type and ramp type. A review of the literature reveals that it is convenient to treat these two separate topics collectively. Current studies are cross-sectional since instances of replacing a ramp or interchange type with another are too rare to facilitate the desired before-after study type for deriving AMF knowledge.

Exhibit 5-1: Resources examined to investigate the safety effect of interchange type

DOCUMENT	DESCRIPTION	COMMENT
(*16*) (Parajuli, B., Persaud, B., Lyon, C., and Munro, J., "Safety Performance Assessment of Freeway Interchanges, Ramps, and Ramp Terminals", Presented at the Road Safety Engineering Management Section of the 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island, (2006))	Developed negative binomial regression models for different interchange categories	Added to synthesis
(*17*) (Bared, J., Powell, A., Kaisar, E., and Jagannathan, R., "Crash Comparison of Single Point and Tight Diamond Interchanges", Journal of Transportation Engineering, Vol. 131(5), pp. 379-381, May 2005)	Compared the safety of 27 diamond interchanges with 13 single point interchanges	Added to synthesis
(*2*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*3*) (Garber, N. J. and Fontaine, M. D., "Guidelines for Preliminary Selection of the Optimum Interchange Type for a Specific Location." VTRC 99-R15, Charlottesville, Virginia Transportation Research Council, (1999))	Studied operational and safety characteristics of various interchange types, 3 years of accident data for 10 interchanges in Virginia.	Suggested by NCHRP 17-18(4). No AMFs; rates and qualitative information added to synthesis.
(*4*) (Khorashadi, A., "Effect of Ramp Type and Geometry on Accidents." FHWA/CA/TE-98/13, Sacramento, California Department of Transportation, (1998))	Analyzed accident rates between ramps of different designs, by urban/rural, and on-ramp vs. off-ramp.	No AMFs; summary information added to synthesis.
(*5*) (Bauer, K. M. and Harwood, D. W., "Statistical Models of Accidents on Interchange Ramps and Speed-Change Lanes." FHWA-RD-97-106, McLean, Va., Federal Highway Administration, (1997))	Negative binomial regression models developed for interchange ramps and speed change lanes based on data from Washington State.	Added to synthesis.
(*6*) (Garber, N. J. and Smith, M. J., "Comparison of the Operational and Safety Characteristics of the Single Point Urban and Diamond Interchanges." FHWA-VA-97-R6, Richmond, Virginia Department of Transportation, (1996))	Compared accident rate, accident type and accident location using 3 years of accident data at 5 diamond interchanges and 8 SPUIs.	Suggested by NCHRP 17-18(4). No AMFs; qualitative information added to synthesis.
(*7*) (Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." Transportation Research Record 1383, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.)	Reviewed literature dealing with the safety of interchange features.	Suggested by NCHRP 17-18(4). No AMFs; accident rates by ramp type added to synthesis.
(Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume IV - Interchanges." FHWA-RD-91-047, Washington, D.C., Federal Highway Administration, (1992))	Same material as Twomey et al. (1993).	Suggested by NCHRP 17-18(4). Not added to synthesis.
(*8*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Some material from Chapter 6 provides insight into interchange treatments.	Cirillo's regression models added to synthesis.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Summarized in Various 1982	Not added to synthesis.
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Same information is covered in Twomey et al. (1993).	Not added to synthesis.
(Cirillo, J. A., Beatty, R. L., Dietz, S. K., Kaufman, S. F., and Yates, J. G., "Interstate System Accident Research Study-I: Three Volumes." Washington, D.C., U.S. Department of Transportation, Federal Highway Administration, (1970))	Provides comparison of pre-interstate to post-interstate safety.	Not added to synthesis.

Treatment: Convert intersection to grade-separated interchange

Elvik and Erke reviewed additional international literature to update the "Handbook ofRoad Safety Measures". The findings of their update meta-analysis were considered medium high, and a MCF of 1.8 was assigned to the standard errors reported.

For converting a four-leg at-grade intersection to a grade-separated interchange, these updated findings show a decrease in accidents in the area of the intersection, as shown in Exhibit 5-2.(*9*) The safety effect of converting a three-leg intersection is also shown in Exhibit 5-2.(*9*)

Converting a three-leg or four-leg signalized at-grade intersection to a grade-separated interchange decreases accidents in the area of the intersection, as shown in Exhibit 5-2.(*9*)

Exhibit 5-2: Safety effects of converting at-grade intersection to grade-separated interchange(9)

Author, date	Treatment	Setting Interchange type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Four-leg intersection Traffic control unspecified	Unspecified	All accidents in the area of the intersection, All severities	0.58	0.10
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Four-leg intersection Traffic control unspecified	Unspecified	All accidents in the area of the intersection, Injury	0.43	0.05
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Four-leg intersection Traffic control unspecified	Unspecified	All accidents in the area of the intersection, Non-injury	0.64	0.14
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Three-leg intersection Traffic control unspecified	Unspecified	All accidents in the area of the intersection, All severities	0.84	0.17
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Three-leg or Four-leg Signalized intersection	Unspecified	All accidents in the area of the intersection, All severities	0.73	0.08
Elvik and Erke, 2007	Convert at-grade intersection to grade-separated interchange	Three-leg or Four-leg Signalized intersection	Unspecified	All accidents in the area of the intersection, Injury	0.72	0.11

NOTE: Based on International studies: Hvoslef 1974; Statens vägverk 1983B; Tie ja vesirakennushallitus 1983; Johansen 1985; Tielaitos 2000; Pajunen 1999; Meewes 2002

Treatment: Safety effect of interchange and ramp type

Elvik and Erke reviewed additional international literature to update the "Handbook of Road Safety Measures". The findings of their update meta-analysis were considered medium high, and a MCF of 1.8 was assigned to the standard errors reported, as shown in Exhibit 5-3.

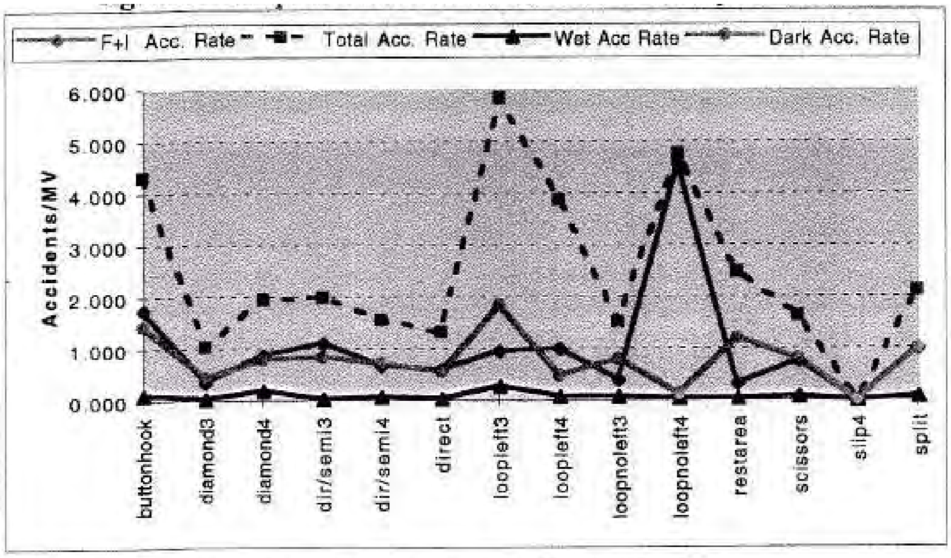
Exhibit 5-3: Safety effects of providing a different interchange type(9)

Author, date	Treatment	Setting Interchange type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Erke, 2007	Provide diamond interchange	Trumpet, direct access, cloverleaf, or directional loop	Unspecified	Truck accidents on ramps, All severities	0.89	0.1
Elvik and Erke, 2007				All accidents in the area of the interchange, All severities	0.93	0.09
Elvik and Erke, 2007		Trumpet, direct access, or cloverleaf		Truck accidents on ramps, All severities	1.43	0.09
Elvik and Erke, 2007		Trumpet interchange		All accidents in the area of the interchange, All severities	0.62	0.2
Elvik and Erke, 2007		Cloverleaf interchange			0.98	0.2
Elvik and Erke, 2007		Directional loop interchange			0.91	0.2
Elvik and Erke, 2007				Truck accidents on ramps, All severities	0.90	0.1
Elvik and Erke, 2007	Provide tight-urban-diamond interchange (TUDI)	Single-point-urban interchange (SPUI)		All accidents in the area of the interchange, All severities	1.02	0.1

NOTE: Based on U.S. studies: Lundy 1967; Cirillo 1968, 1970; Yates 1970; Bauer, Harwood 1998; Janson et al. 1998; Bared, Giering & Warren 1999; Khorashadi 1998; Golob, Recker & Alvarez 2004; McCartt et al. 2004; Lee et al. 2002 and International studies: Wold 1995; Pajunen 1999; Tielaito 2000

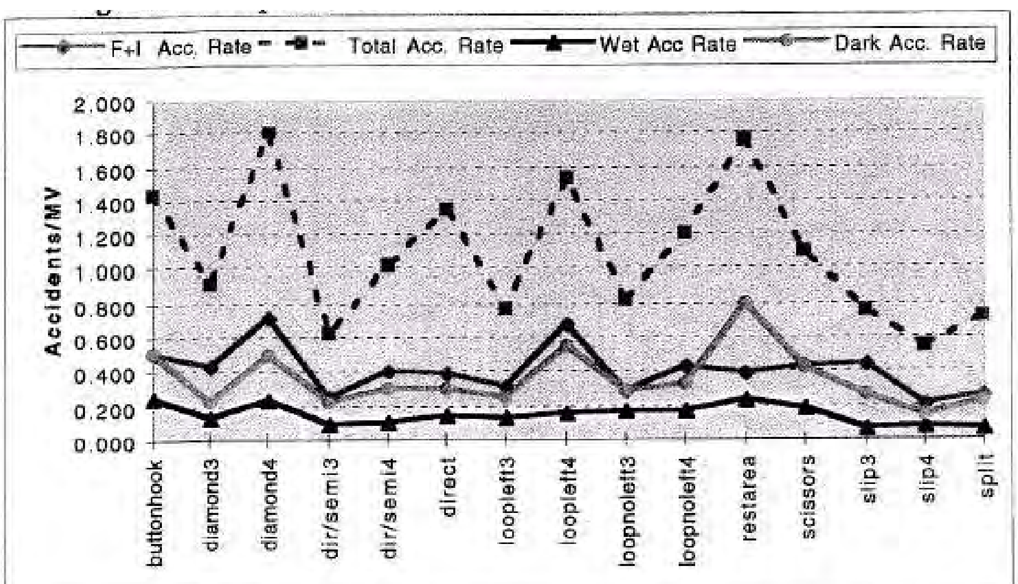
Khorashadi (1998) analyzed accident rates (accidents per million vehicles entering or exiting a ramp) between ramps of different designs and disaggregated by urban/rural area and on-ramp vs. off-ramp (*4*). Accident types studied included fatal, fatal+injury, total, wet, and dark accidents. A total of 13,325 ramps were used with 3 years of data. Analysis of Variance (ANOVA) and Analysis of Covariance (ANCOVA) methods were used and the effects of traffic volumes and district location were taken into account. Exhibit 5-4 to Exhibit 5-7 show accident rates by area type and on-ramp vs. off-ramp.

Exhibit 5-4: Comparison of Accident Rates for Off-Ramps in Rural Areas (Figure 16 of (4))



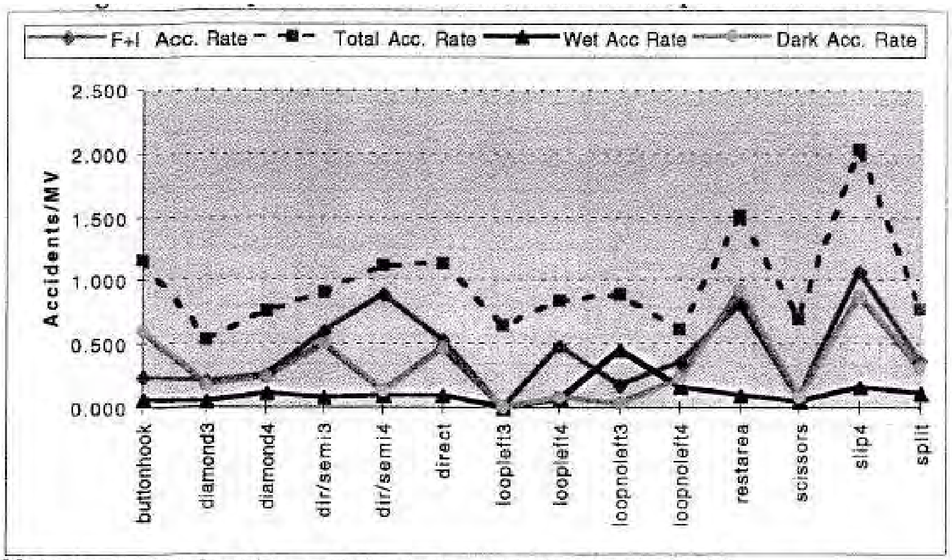
Notes: 1) For suffix 3 and 4 in ramp designation (i.e. loopleft3, ect.) see section 3.2.
2) dir/semi = Direct or Semi-direct Connector; loopnoleft = Loop with no Left Turn; loopleft = Loop with Left Turn; buttonhook= Button Hook; twoway = Two-Way Ramp; restarea= Rest Areas, Vista Points and Truck Scales

Exhibit 5-5: Comparison of Accident Rates for Off-Ramps in Urban Areas (Figure 17 of (4)



* (With Ramp Volume Adjusted)

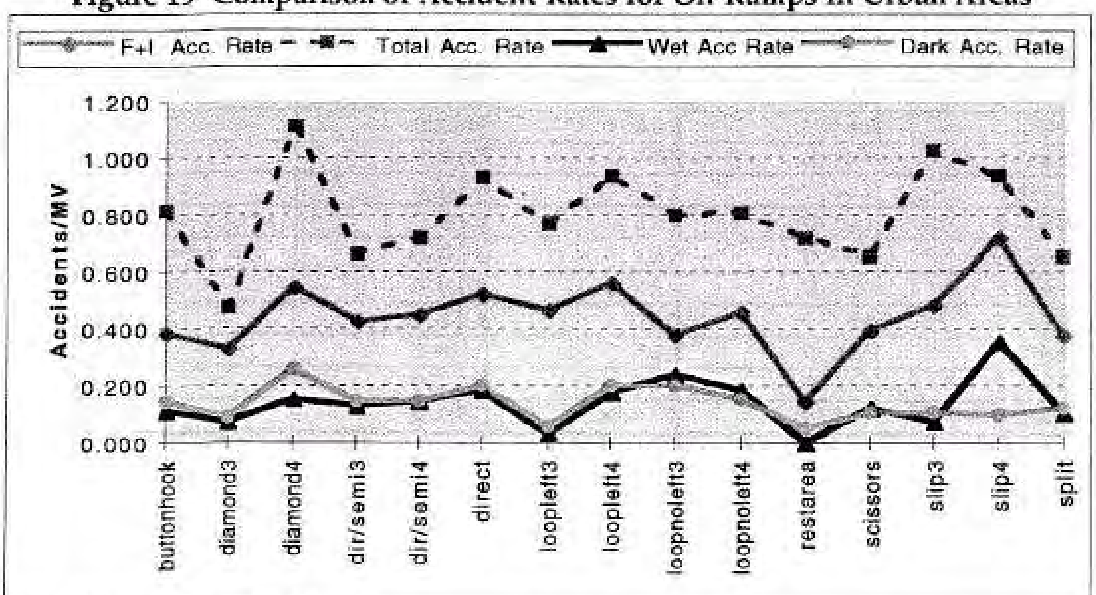
Exhibit 5-6: Comparison of Accident Rates for On-Ramps in Rural Areas (Figure 18 in (4)



Notes: 1) For suffix 3 and 4 in ramp designation (i.e. loopleft3, ect.) see section 3.2.
2) dir/semi = Direct or Semi-direct Connector; loopnoleft = Loop with no Left Turn; loopleft = Loop with Left Turn; buttonhook= Button Hook; twoway = Two-Way Ramp; restarea= Rest Areas, Vista Points and Truck Scales

Exhibit 5-7: Comparison of Accident Rates for On-Ramps in Urban Areas (Figure 19 in (4))

Figure 19 Comparison of Accident Rates for On-Ramps in Urban Areas



* (With Ramp Volume Adjusted)

Garber and Fontaine (1999) studied the operational and safety characteristics of various interchange types, including 3 years of accident data for 10 interchanges in Virginia (*3*). These 10 sites consisted of 2 diamond, 3 full cloverleaf, 3 partial cloverleaf, and 2 single point urban interchanges (SPUIs). Accident data were collected up to 150 ft from the interchange and on all ramps. Differences in accident rates (accidents/100 million entering vehicles) were compared and tested using the student's t-test methodology. Due to the small data sample size, none of the findings were deemed conclusive by Garber and Fontaine. The only statistically significant accident rate differences were for PDO and total accident rates, where partial cloverleafs exhibited a lower accident rate than SPUIs. Exhibit 5-8 shows the distribution of accident types at the four interchange types. Exhibit 5-9 shows the distributions of accident locations at the four interchange types.

Exhibit 5-8: Accident Type Distribution (Figure 21 of (3))

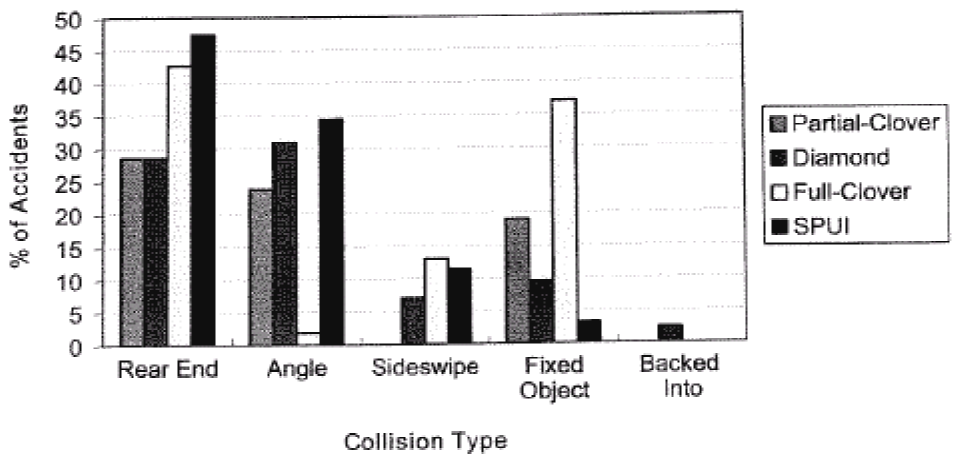


Exhibit 5-9:Accident Location Distribution (Figure 22 of (3))

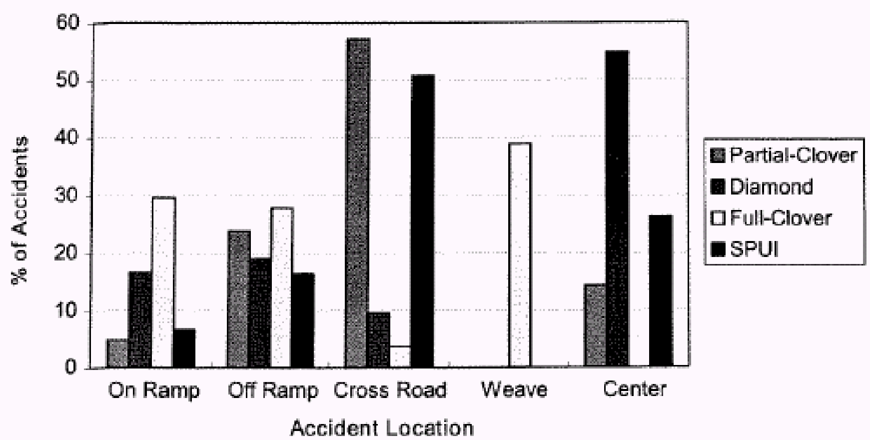


Figure 22. Accident Location Distribution

Key conclusions made by Garber and Fontaine were (*3*):

- Angle accidents are less common at full cloverleafs (2%) than at partial cloverleafs (24%) and SPUIs (34%), likely due to the absence of turning movements at full cloverleafs.
- SPUIs had a larger percentage of sideswipe accidents (12%) than diamond (7%) or partial cloverleaf interchanges.
- The full cloverleaf had a larger percentage of fixed object accidents (37%) than any other interchange type.

The most common accident locations by interchange type were:

- Diamond – center of ramp intersection (54.8%)
- SPUIs – crossroad (50.8%)
- Partial cloverleaf – crossroad (57.1%)
- Full cloverleaf – weaving area (38.9%)

Further guidance with respect to safety concerns, according mostly to the literature review, included (*3*):

- Loop ramps should be avoided where possible due to a poorer safety record than other ramp types.
- Weaving areas are a high concern for safety, especially when collector-distributor roads are not provided.
- When two roads intersect at a large skew angle, use of the SPUI is generally not recommended due to reduced sight distance.
- Interchange uniformity should be considered when selecting interchange types. Uniformity can aid drivers in where they need to enter or exit reducing confusion.

Likewise, Garber and Smith's (1996) earlier study compared the accident rate, accident type and accident location using 3 years of accident data at 5 diamond interchanges and 8 single point urban interchanges (SPUIs) (*6*). No statistically significant differences were found in accident severity between the two interchange types. In conclusion, when permitted left-turn phasing is used at diamond interchanges, the proportion of angle and center of intersection accidents is higher than at the SPUIs. Signalized intersections on the crossroad that are adjacent to interchanges have a poorer safety record when the downstream signal is not coordinated with the interchange signal and when there is inadequate clear distance to the intersection. This will be discussed further in Section 5.1.5.1 [Future Edition]. Exhibit 5-10 shows the distribution of accident locations between diamond and SPUI interchanges. Exhibit 5-11 shows the distributions of accident type. Exhibit 5-12 shows the accident rate by accident type.

Exhibit 5-10: Accident Location Distribution (Figure 18 of (6))

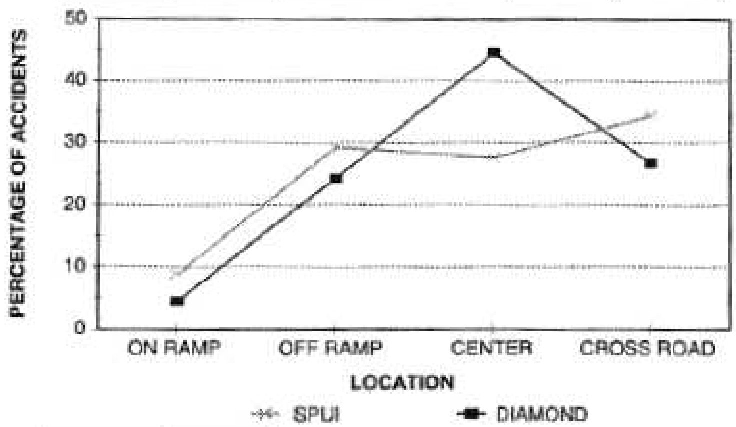


Exhibit 5-11: Accident Type Distribution (Figure 19 of (6))

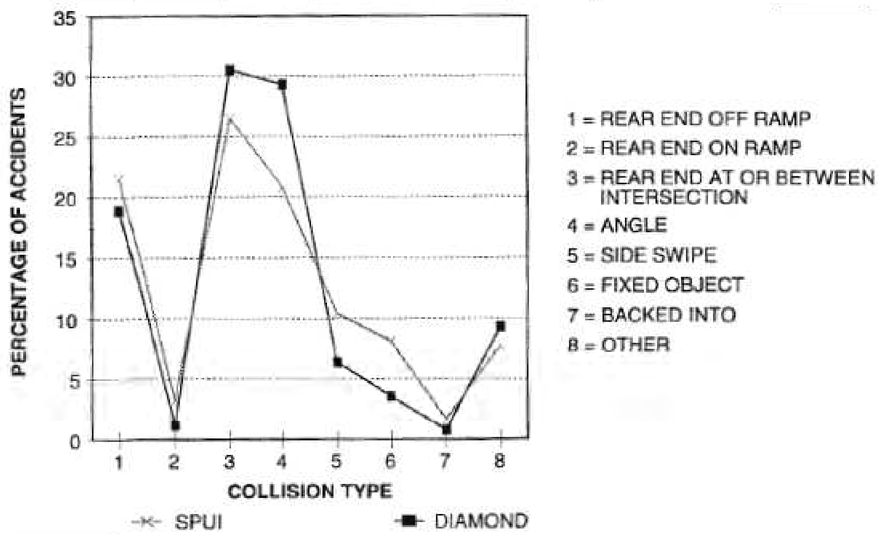
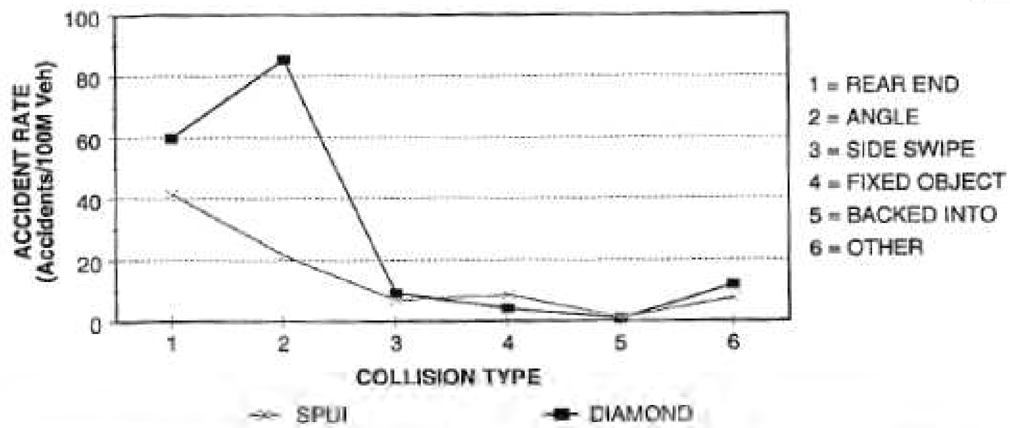


Exhibit 5-12: Accident Rates by Accident Type (Figure 20 of (6))



Tests of proportionality by Garber and Smith indicated the following statistically significant differences (*6*):

- The proportion of on-ramp accidents is greater at SPUI than diamond interchanges.
- The proportion of off-ramp accidents is greater at SPUI than diamond interchanges.
- The proportion of accidents in the center of the intersection is greater at diamond than SPUI interchanges.
- The proportion of on-ramp rear-end accidents at SPUIs is greater than at diamond interchanges.
- The proportion of sideswipe and fixed object accidents at SPUIs is greater than at diamond interchanges.
- The proportion of angle accidents at is greater at diamond interchanges than at SPUIs.

Garber and Smith note that where SPUIs are used, the signalization of on-ramp flows should be avoided as an increase in rear-end on-ramp accidents may result (*6*).

Twomey et al. (1993) reviewed literature dealing with the safety of interchange features (*7*). Taken from their paper, Exhibit 5-13 shows accident rates by type of ramp. Diamond interchange ramps have the lowest accident rate; however, the rates do not include crossroad and ramp intersection accidents. Diamond ramps, cloverleaf ramps with collector-distributors, direct connections and cloverleaf loops with collector-distributors typically have lower accident rates than scissor ramps and left-side ramps. Buttonhook ramps, loops without collector-distributors, cloverleaf ramps without collector-distributors and trumpet ramps are between these high and low groups. Exhibit 5-14 indicates that accident rates increase as interchange spacing decreases in urban areas.

Exhibit 5-13:Accident Rates by Type of Freeway Ramp (Table 6 of (7))

Ramp Type	On	Off	On & Off
Diamond Ramps	0.40	0.67	0.53
Cloverleaf Ramps with Coll-Dist Roads[a]	0.45	0.62	0.61
Direct Connections	0.50	0.91	0.67
Cloverleaf Loops with Coll-Dist Roads[a]	0.36	0.40	0.69
Buttonhook Ramps	0.64	0.96	0.80
Loops with Coll-Dist Roads	0.78	0.88	0.83
Cloverleaf Ramps w/o Coll-Dist Roads	0.72	0.95	0.84
Trumpet Ramps	0.84	0.85	0.85
Scissor Ramps[b]	0.88	1.48	1.28
Left Side Ramps	0.93	2.19	1.91
Average	0.59	0.95	0.79

NOTE: Accident rates are per million vehicles.
[a]Only the On & Off rate includes the accidents occurring on the collector-distributor roads.
[b]A ramp that has opposing traffic crossing the ramp traffic under stop sign control.

Exhibit 5-14: Accident Rates by Proximity to Interchange Ahead or Behind (Table 8 of (7))

EXIT SIDE

Dist. to exit-ramp nose ahead

Urban	No. Acc.[a]	Acc. Rate[b]
Less than .2 miles	722	131
.2-.4 miles	1,209	127
.5-.9 miles	786	110
1.0-1.9 miles	280	75
2.0-3.9 miles	106	63
4.0-7.9 miles	19	69
More than 8 miles[c]	--	--
Rural		
Less than .2 miles	160	76
.2-.4 miles	459	75
.5-.9 miles	559	69
1.0-1.9 miles	479	69
2.0-3.9 miles	222	68
4.0-7.9 miles	46	62
More than 8 miles[c]	--	--

ENTRANCE SIDE

Dist. to exit-ramp nose ahead

Urban	No. Acc.[a]	Acc. Rate[b]
Less than .2 miles	425	122
.2-.4 miles	1,156	126
.5-.9 miles	1,055	105
1.0-1.9 miles	278	84
2.0-3.9 miles	151	59
4.0-7.9 miles	200	75
More than 8 miles[c]	--	--
Rural		
Less than .2 miles	117	80
.2-.4 miles	482	82
.5-.9 miles	560	72
1.0-1.9 miles	435	64
2.0-3.9 miles	169	51
4.0-7.9 miles	52	40
More than 8 miles[c]	--	--

[a] No. of Accidents.
[b] Accidents per 100 Million Vehicle-Miles.
[c] No data available.

Bauer and Harwood (1997) developed negative binomial regression models for accidents on interchange ramps and speed change lanes (*5*). Data from the State of Washington were used to develop separate models for total and fatal+injury accidents. The database analyzed included five types of ramp configurations:

1. Diamond
2. Parco loop
3. Free-flow loop
4. Outer connection
5. Direct or semi-connection

The following combinations of elements were successfully modeled:

- Ramp proper segments (off- and on-ramps combined and off-ramps only)
- Entire ramps (off- and on-ramps combined and off-ramps only)
- Acceleration lanes
- Deceleration lanes
- Entire ramps plus adjacent speed-change lanes

Ramp proper segments are sub-segments on a ramp with a constant cross-section. These ramp proper segments were defined in an attempt to relate accident frequency to cross-section geometrics. Entire ramps include whole ramps from the entry/exit gore to the exit terminal/merge gore.

The best explanatory variable for all models was the ramp Annual Average Daily Traffic (AADT). Other significant variables in some models included mainline AADT, rural/urban location, ramp type (on/off), ramp configuration, and length of ramp plus speed-change lane. Other variables attempted included travelway width for ramps and speed-change lanes, right shoulder width for ramps and speed-change lanes, left-shoulder width for ramps, ramp grade (upgrade/downgrade), and radii of horizontal curves on ramps (*5*).

The model form used by Bauer and Harwood is shown in Equation 5-1.

Equation 5-1: Negative binomial regression model form for accidents on interchange ramps and speed change lanes (5)

$$\text{Accident frequency} = \text{alpha}(\text{AADT})^{b0}\exp(b_1X_1+b_2\,X_2+\ldots+b_nX_n))$$

Where alpha and $b_0 \ldots b_n$ are the estimated parameters

The relative effects estimated by Bauer and Harwood are not intended for use as AMFs. As noted by the original authors, "The models presented here, which focus on expected values, are not intended to predict which specific ramps will have extremely high accident frequencies". Rather, these models may be calibrated by agencies for predicting the safety performance of ramps of various types. Nevertheless, based on the models, the following trends are noted (*5*):

- Results for ramp proper, entire ramps and ramps and speed change lanes indicate that off-ramps have a higher accident frequency than on-ramps.
- For AADT from 27 veh/day to 24,365 veh/day, ramps with one lane experience fewer accidents than ramps with 2 or more lanes.
- For off-ramps, the configuration from lowest to highest accident frequency for ramp proper is:
    - direct/semi-direct connectors
    - diamond
    - loop
    - outer connectors
- For on-ramps, the configuration from lowest to highest accident frequency for ramp proper is:
    - direct/semi-direct connectors
    - outer connectors
    - loop
    - diamond
- Without accounting for on- vs. off-ramp, the expected accident frequencies by ramp configuration vary although direct/semi-direct, free-flow and diamond interchanges are low to lowest in that order.

Bared et al. (2005) compared the intersection related crash frequencies between single point interchanges (SPI) and diamond interchanges (DI) (*17*). Data from 27 DIs from the state of Washington were used to estimate a negative binomial regression model relating total crash frequency and injury/fatal crash frequency with cross road AADT and off-ramp AADT. In addition, crash and traffic volume data were collected from 13 SPIs from four States: Maryland, California, Missouri, Washington, and Virginia. Regression models were not estimated for the SPI group. None of the sites had frontage roads and none of them allowed through traffic from the off ramps onto corresponding on ramps. The observed crashes of the individual SPI sites were compared with the expected crashes derived from the regression models estimated for the DI sites. The comparison was done using a nonparametric Wilcoxon signed-rank test. For total crashes, the comparison did not reveal significant differences. However, for injury and fatal crashes, the SPI was found to be safer compared to the DI.

Parajuli et al. (2006) developed negative binomial regression models for three groups of interchanges on Ontario freeways (*16*):

Group 1 (133 sites): Full diamond, Partial Cloverleaf (Parclo), Partial Loop (Loop), and Service Road

Group 2 (104 sites): Parclo (4-Quad), Loop (4-Quad), Full Cloverleaf

Group 3 (70 sites): Trumpet, Direct Link, Freeway to Freeway, Other

The influence length of each interchange was considered as 1 km on either side of the interchange. If two interchanges were closely spaced (less than 2 km), the influence length for each was taken as one half of the distance between them. Crash data from 1997 to 2002 were included in the analysis. The main objective of the regression models was to use them as predictive tools as part of network screening. Models for mainline crashes included AADT and section length in kilometers in the following form (Equation 5-3):

Equation 5-2: Negative binomial regression model form for mainline crashes (16)

$$Collisions / year = a(AADT)^b e^{c(length)}$$

where, a, b, and c are parameters estimated from the data.

Exhibit 5-15 shows the parameter estimates and standard errors from the models estimated along with the average AADT and number of crashes for each group.

Exhibit 5-15: Regression models for freeway mainline crashes for various interchange groups (Parajuli et al. 2006 (16))

Crash Type	Parameter	Group 1 (133 sites)		Group 2 (104 sites)		Group 3 (70 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
Injury and Fatal	ln(a)	-7.0564	0.7881	-10.9230	0.6720	-10.0818	0.9062
	b	0.7732	0.0578	1.1302	0.0484	0.9898	0.0685
	c	0.1407	0.1780	0.1801	0.1617	0.5680	0.2002
	φ	0.2634	0.0369	0.1632	0.0251	0.3072	0.0563
Property damage only	ln(a)	-8.4681	0.6107	-11.3698	0.6222	-10.6217	0.8347
	b	0.9949	0.0467	1.2212	0.0459	1.1301	0.0639
	c	0.2834	0.1292	0.5871	0.1409	0.7248	0.1831
	φ	0.1784	0.0233	0.1458	0.0208	0.2944	0.0500

Crash Type	Parameter	Group 1 (133 sites)		Group 2 (104 sites)		Group 3 (70 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
AADT	Minimum	8,833		9,250		6,858	
	Average	82,194		135,374		85,157	
	Maximum	383,833		428,633		373,000	
Crash counts	Injury/Fatal	4,896		10,906		3,270	
	PDO	16,546		39,303		12,169	

The models in Exhibit 5-15 were used to developed graphs showing the relationship between crash frequency on the mainline and AADT. It is clear that for high AADT values (say exceeding 150,000), interchanges in Group 2 have the highest number of mainline crashes, and this is true for PDO and injury/fatal crashes. Group 3 consistently has the fewest number of crashes. This finding is not very surprising because interchanges in Group 2 are probably the most complex in terms of the number of access points with the mainline of the freeway, and interchanges in Group 3 have the least number of access points. It should be emphasized that these models are not intended to be causal, and hence, definitive conclusions regarding the safety of interchange types cannot be made from these models.

Exhibit 5-16: Relationship between mainline injury and fatal crashes and AADT for different interchange groups (derived from Parajuli et al. 2006 (16))

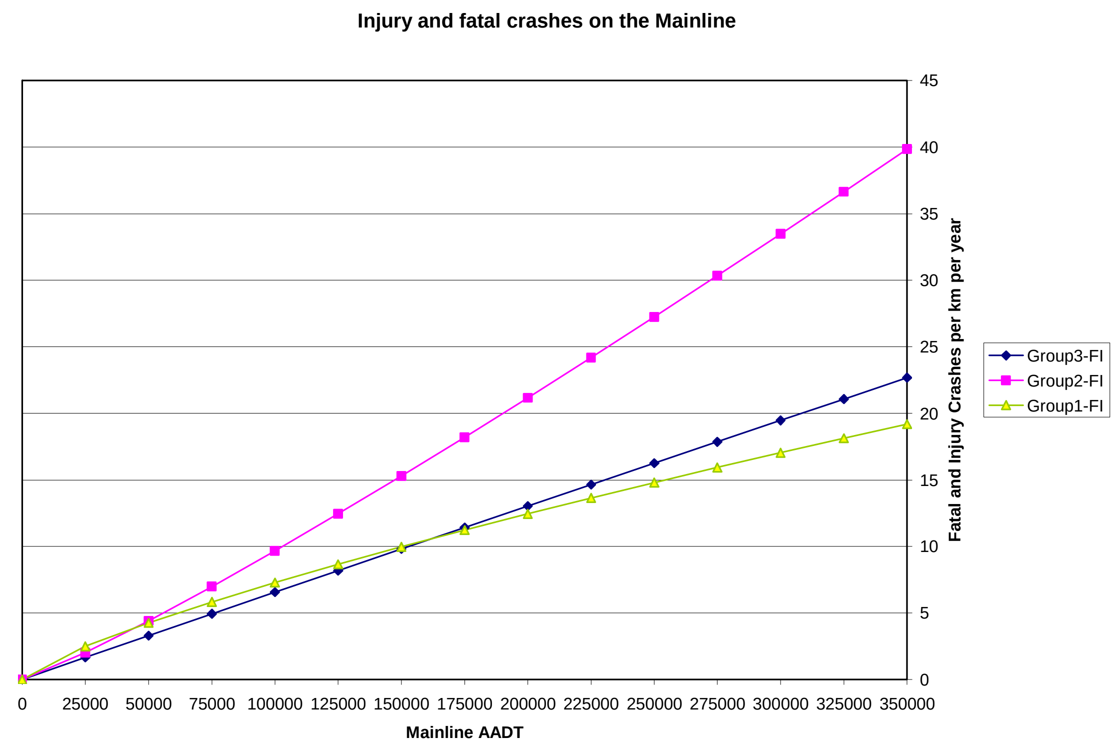
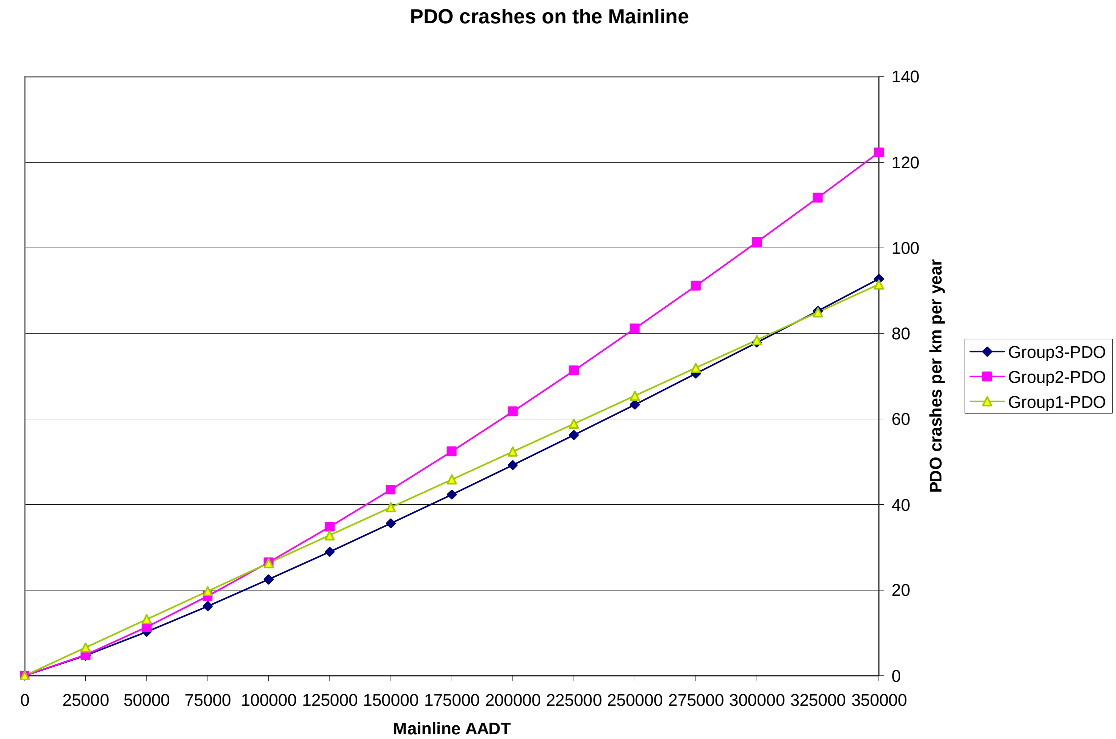


Exhibit 5-17: Relationship between mainline PDO crashes and AADT for different interchange groups (derived from Parajuli et al. 2006 (16))



Cirillo et al. (1969) developed a series of regression models from interstate accident and geometry data for various interchange types.(*8*) ADT was found to be the key predictor of accidents at interchanges. Geometric elements included in the models include: lane width, shoulder width, lighting intensity, and guardrail presence. These models are summarized in Exhibit 5-18. These models cannot be used to develop AMFs for specific treatments.

Exhibit 5-18: Regression models for various interchange types (Cirillo et al. (1969) (8))

Model	**Number of Observations (N)**	**Square of Multiple Correlation Coefficient (R^2)**
Full Cloverleaf (with no collector-distributor roadway)		
Y = -3.7 + 1.3X – 0.025C	186	0.80
Partial Cloverleaf		
Y = -1.6 + 0.24X + 2.9Z – 0.17F	191	0.69
Three-leg or Trumpet		
Y = 0.41 + 0.20X + 0.17J	160	0.53
Full Diamond		

Model	Number of Observations (N)	Square of Multiple Correlation Coefficient (R^2)
Y = -1.0 + 0.31X + 2.0Z – 1.0A + 0.14B – 0.0045D – 0.11F – 0.51G + 0.61H	681	0.89
Half Diamond		
Y = -0.64 + 0.15X + 1.27 + 0.50A + 0.14B – 0.0064D	94	0.86
Full Slip Ramp		
Y = 2.9 + 2.0X – 0.067C – 0.0013E	96	0.76
Where: Y = Number of Accidents X = Average daily traffic volume (thousands of vehicles) Z = Average daily traffic volume exiting the interstate (thousands of vehicles) A = X x Number of businesses per one hundred feet on crossroad B = X x Area type (1 = rural, 0=urban) C = X x Percent commercial vehicles, day D = X x Percent commercial vehicles, night E = X x Size of interchange (feet) ("Index" of area consumed by interchange) F = X x Lighting intensity (foot-candles) G = X x Type of crossroad (1=divided, 0=undivided) H = X x Number of lanes in crossroad (1=four or more, 0=two) J = X x Type of interchange (1=trumpet, 0=three-leg)		

Other information provided in the 1982 synthesis of interchange safety include:(*8*)

- Woods et al. concluded that all freeway exists would be expected on the right in advance of the interchange structure, based on diagnostic field studies in Texas
- A study by Lundy of the relative safety of different interchange ramps using accident rates indicates that diamond and directional interchanges have the best safety performance, while loop and cloverleaf ramps without collector-distributor roads, trumpet, scissors, and left-hand ramps have the poorest safety performance. This study included accidents from on- and off-ramps, and excluded crossroad accidents and freeway mainline accidents within the interchange area.

Treatment: Crossroad over versus under the freeway

Elvik and Erke reviewed additional international literature to update the "Handbook ofRoad Safety Measures". The findings of their update meta-analysis were considered medium high, and a MCF of 1.8 was assigned to the standard errors reported, as shown in Exhibit 5-19.

Exhibit 5-19: Safety effects of designing an interchange with crossroad above freeway(9)

Author, Date	Treatment	Setting Interchange type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Erke, 2007	Design diamond, trumpet or cloverleaf interchange with crossroad above freeway	Unspecified	Unspecified	All accidents in the area of the interchange, All severities	0.96	0.1

NOTE: Based on U.S. studies: Lundy 1967; Cirillo 1968, 1970; Yates 1970; Bauer, Harwood 1998; Janson et al. 1998; Bared, Giering & Warren 1999; Khorashadi 1998; Golob, Recker & Alvarez 2004; McCartt et al. 2004; Lee et al. 2002 and International studies: Wold 1995; Pajunen 1999; Tielaito 2000

Operational studies indicate that it is more desirable to design interchanges with the crossroad over (above) the freeway.(*8*) Two key reasons are:

1. The crossroad over the freeway normally results in a longer sight distance to the exit ramp and gore area. The freeway over the crossroad (less desirable) normally results in a shorter sight distance to the exit ramp and gore area due to the freeway vertical grade and/or vertical crest.
2. The crossroad over the freeway allows gravity to assist the operation of both accelerating vehicles (the on-ramp has a down-grade) and decelerating vehicles (the off-ramp has an up-grade). In addition, the resulting grades generally provide longer sight distances.

Discussion: Modify interchange spacing

Decreasing interchange spacing appears to increase accidents.(*7*, *18*, *19*) However, the safety effect is not certain at this time.

Discussion: Provide right-hand exit and entrance ramps

Leisch et al. state that providing left-hand exits on the freeway system violates the concepts of operational uniformity and design consistency. North American drivers tend to anticipate exits on the right-hand side, and select lanes accordingly. As a result, the occasional left-hand exit ramps violates driver expectancy, which may result in evasive maneuvers, lane changes, and a mix of decelerating traffic destined for the left-hand exit with high-speed straight-through and passing traffic in the left lane.(*8*) Leisch et al. cite three studies of left-hand versus right-hand exit ramps, concluding that left-hand exits have a poorer safety performance than right-hand exits (Lundy, Northwestern University, Taylor et al.).

Similarly, Leisch et al. state that providing left-hand entrances to the freeway violates driver expectation. Drivers in the left lane of a freeway do not expect vehicles to enter the freeway and merge into their lane. Also, as traffic in the left lane is generally high-speed straight-through and passing traffic, and entering drivers must merge at a higher speed than if the merging occurred with right lane traffic.(*8*) These concerns may be increased for low speed or heavy trucks. Leisch et al. cite three studies of left-hand versus right-hand entrance ramps, concluding that left-hand entrances have a poorer safety performance than right-hand entrances (Lundy, Northwestern University, Taylor et al.).

Drivers expect exit and entrance ramps on freeways to be on the right-hand side of the freeway.(*8*) Providing left-hand exit or entrance ramps has a negative effect on safety. However, the safety effect is not certain at this time.

Conclusions

The results of the meta-analysis by Elvik and Vaa provide AMFs for modifying various interchange types to a diamond interchange.

The Khorashadi et al. study is a simple cross-sectional one in which traffic volume was accounted for using the accident rate procedure that tends to give misleading results. Thus, the conclusions are not practical in terms of providing quantitative or qualitative knowledge on the relative safety of various ramp types. A similar difficulty exists for the Garber et al. studies as well as those reviewed by Twomey et al.

The Bauer et al. study provides regression models with correlated and omitted variables, and their use to derive AMFs is therefore questionable. These models can be used to make inferences about the relative safety of various ramp types, but these inferences cannot easily be corroborated with intuition since it is not intuitively clear how ramp types differ in safety.

The models developed by Bauer et al. were intended as predictive models of the safety performance of ramps and interchanges (rather than causal models from which AMFs could be derived) and could and should be used as such if deemed appropriate in Part 3 of the HSM. The Garber et al. study, though a modern-day one, is, by the authors' own admission, inconclusive. This is compounded by the methodology applied that is known to lead to incorrect conclusions.

The Cirillo et al. regression models cannot be used to develop AMFs for specific treatments.

In summary, there is little or no AMF information for interchange and ramp type, but there are nevertheless useful models for predicting the safety performance of ramps of various types.

5.1.2. Merge/Diverge Areas

Merge/diverge areas can be loosely defined as those portions of the highway at an interchange where vehicles entering and exiting must change lanes to continue traveling in their desired direction. The following terms, as defined in AASHTO's Policy on Geometric Design (*1*), will be used in this discussion:

- Weaving sections: "highway segments where the pattern of traffic entering and leaving at contiguous points of access results in vehicle paths crossing each other; may occur within an interchange, between entrance ramps, followed by exit ramps of successive interchanges, and on segments of overlapping roadways" (Pg 823).
- Speed change lanes: auxiliary lane that provides for vehicles to accelerate or decelerate; part of the ramp terminal area; taper or parallel (Pg 848).

In addition, as defined in the Highway Capacity Manual (2000) (*10*):

- Interchange ramp terminal = a junction with a surface street to serve vehicles entering or exiting a freeway (plural is "terminals").
- Entrance ramp = a ramp that allows traffic to enter a freeway.
- Exit ramp = a ramp for traffic to depart from a freeway.
- Acceleration lane = a paved auxiliary lane, including tapered areas, allowing vehicles to accelerate when entering the through-traffic lane of the roadway.
- Deceleration lane = a paved auxiliary lane, including tapered areas, allowing vehicles leaving the through-traffic lane of the roadway to decelerate.
- Merge = a movement in which two separate lanes of traffic combine to form a single lane without the aid of traffic signals or other right-of-way controls.
- Diverge = a movement in which a single lane of traffic separates into two lanes without the aid of traffic control devices.

Exhibit 5-20: Resources examined to investigate the safety effect of merge and diverge areas at interchanges

DOCUMENT	DESCRIPTION	COMMENT
(*20*) (Sarhan, M., Hassan, Y., and Abd El Halim, A.O., "Design of Freeway Speed Change Lanes: Safety-Explicit Approach", Presented at the 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2006)	Developed negative binomial regression models to study the relationship between crash frequency and length of acceleration and deceleration lanes.	Added to synthesis.
(*2*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis.
(Smiley, A., "Driver Performance at Interchanges." (2004))	The paper analyses drivers' tasks at interchanges (entering, through, exiting).	Not added to synthesis.
(Janson, B., Kononov, J., Awad, W., Robles, J., and Pinkerton, B., "Effects of Geometric Characteristics of Interchanges on Truck Safety." CDOT-DTD-R-99-3, Denver, Colorado Department of Transportation, (1999))	Used crash data from WA, CO, and CA to identify relationships between truck accidents and geometric characteristics of interchanges including merge/diverge areas.	Suggested by NCHRP 17-18(4). Not added to synthesis.
(Bared, J., Giering, G. L., and Warren, D. L., "Safety Evaluation of Acceleration and Deceleration Lane Lengths." ITE Journal, Vol. 69, No. 6, Washington, D.C., Institute of Transportation Engineers, (1999) pp. 50-54.)	This reference reports same models as Bauer and Harwood (1997).	Suggested by NCHRP 17-18(4). Not added to synthesis.
(Khorashadi, A., "Effect of Ramp Type and Geometry on Accidents." FHWA/CA/TE-98/13, Sacramento, California Department of Transportation, (1998))	No analysis of merge/diverge areas.	Not added to synthesis.
(*5*) (Bauer, K. M. and Harwood, D. W., "Statistical Models of Accidents on Interchange Ramps and Speed-Change Lanes." FHWA-RD-97-106, McLean, Va., Federal Highway Administration, (1997))	Negative binomial regression models developed for interchange ramps and speed change lanes based on data from Washington State.	Suggested by NCHRP 17-18(4). Added to synthesis.
(*7*) (Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." Transportation Research Record 1383, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.)	Reviewed literature dealing with the safety of interchange features.	Suggested by NCHRP 17-18(4). Accident rates by interchange unit added to synthesis, with qualitative observations by authors.
(Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume IV - Interchanges." FHWA-RD-91-047, Washington, D.C., Federal Highway Administration, (1992))	Same material as Twomey et al. (1993)	Not added to synthesis.
(*8*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Reviewed literature dealing with the safety of interchange features.	Suggested by NCHRP 17-18(4). Added to synthesis.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Summarized in Various 1982	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*11*) (Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	Reviewed available literature on merge, diverge, and weaving areas.	Discussion of findings added to synthesis.

Discussion: Accident experience of merge/diverge areas

Bauer and Harwood (1997) developed negative binomial regression models for accidents on interchange ramps and speed change lanes (*5*). Data from the State of Washington were used to develop separate models for total and fatal+injury accidents. The database analyzed included five types of ramp configurations:

1. Diamond
2. Parco loop
3. Free-flow loop
4. Outer connection
5. Direct or semi-connection

Accidents on acceleration and deceleration lanes were modeled separately from ramp accidents. Separate models were developed for accidents on acceleration and deceleration lanes including ramp accidents. Lanes associated with a weaving area, lane drops or lane additions were not considered in the models. Left-side ramps were also excluded.

The model form used is shown in Equation 5-3.

Equation 5-3: Negative binomial regression model form for accidents on interchange ramps and speed change lanes (5)

$$\text{Accident frequency} = \text{alpha}(\text{AADT})^{b0}\exp(b_1X_1+b_2X_2+\ldots+b_nX_n))$$

where alpha and $b_0 \ldots b_n$ are the estimated parameters.

Exhibit 5-21 shows the estimated parameter values, their 90% confidence intervals, and the relative effects of each variable included in the final models. The relative effect indicates the expected change in accident frequency for a unit change in that variable. Only those variables related to the merge and diverge areas are reported here. Exhibit 5-22 shows results for the speed-change lane length variable from models for the entire ramp area and speed change lane.

As noted by the original authors, these relative effects are not intended for use as AMFs, “The models presented here, which focus on expected values, are not intended to predict which specific ramps will have extremely high accident frequencies”. Rather, these models may be calibrated by agencies for predicting the safety performance of ramps of various types. Nevertheless, based on the models, the following trends are noted (*5*):

- For every 1 ft increase in right shoulder width on deceleration lanes, the total accident frequency is predicted to increase by 10 percent.
- Total accident frequencies are less in rural areas than urban areas for both acceleration and deceleration lanes.
- As the length of acceleration lane increases, accidents are expected to increase. However, this is natural in that a longer length results in greater exposure. To fully

understand the effects of speed-change lanes, all accidents, including those on the ramp and in weaving areas, should be considered. Indeed, the models for entire ramp areas and speed-change lanes indicate decreases of 93% and 91% for total and fatal+injury accidents respectively for an increase of 1 mile in the speed-change lane (Exhibit 5-22).

Exhibit 5-21: Model Results for Speed-Change Lanes (5)

Independent variable	Ramp Area	Total Accidents		F+I Accidents	
		Estimate (90% C.I.)	Relative Effect (90% C.I.)[1]	Estimate (90% C.I.)	Relative Effect (90% C.I.)[1]
Right shoulder width (ft)	Deceleration Lane	0.09 (0.02 to 0.17)	1.094 (1.020 to 1.185)		
Area type Rural Urban	Acceleration Lane	-0.59 (-1.14 to -0.04) 0	0.55 (0.320 to 0.961) -		
	Deceleration Lane	-1.21 (-1.88 to -0.60) 0	0.298 (0.152 to 0.549) -		
Length of speed-change lane (mi)	Acceleration Lane	6.88 (4.56 to 9.29)	972.6 (95.58 to 10829)	5.32 (2.64 to 8.15) [c]	204.38 (14.01 to 3463)

[c] diamond on-ramps only

[1] Relative effect indicates the expected percentage change in accident frequency for a unit change in that variable. These values cannot be used to develop AMFs.

Exhibit 5-22: Model Results for Entire Ramps and Speed-Change Lanes (5)

Independent variable[a]	Ramp Area	Total Accidents		F+I Accidents	
		Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]	Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]
Length of speed-change lane (mi)	Entire Ramp and Speed-Change Lane	-2.59 (-4.50 to -0.69)	0.075 (0.011 to 0.50)	-4.42 (-6.49 to -2.36)	0.012 (0.002 to 0.094)

[a] variables for Entire Ramp and Speed Change Lane are significant at 20% level

[c] diamond on-ramps only

[1] Relative effect indicates the expected percentage change in accident frequency for a unit change in that variable. These values cannot be used to develop AMFs.

Bauer and Harwood (1997) also note that certain geometric design variables were not found to have a statistically significant relationship to accident frequency, and based on their study are not ultimately recommended for use, including: traveled-way width for ramps and speed change lanes, right shoulder width for ramps and speed change lanes, left shoulder width for ramps, ramp grade, radii of horizontal curves on ramps.(*5*)

Twomey et al. (1993) reviewed literature dealing with the safety of interchange features (*7*). Exhibit 5-23 shows accident rates by interchange unit, separately for rural and urban interchanges. Twomey et al. note that the safety of entrance and exit terminals improves with geometric designs providing acceleration lanes in excess of 800 ft, deceleration lanes in excess of 900 ft, and weaving areas in excess of 800 ft.

Exhibit 5-23: Accident Rates by Interchange Unit and Area Type (Table 7 of (7)

TABLE 7 Accident Rates by Interchange Unit and Area Type (4)

RURAL

Interchange Unit	Vehicle Miles (100 Mil.)	No. Accidents[a]	Accident Rate[b]
Deceleration lane	2.51	348	137
Exit Ramp	0.57	199	348
Area between speed change lanes	6.52	554	85
Entrance Ramp	0.59	95	161
Acceleration lane	3.68	280	76
Acceleration - deceleration lane	0.49	87	116
Total	14.36	1,563	109[c]

URBAN

Interchange Unit	Vehicle Miles (100 Mil.)	No. Accidents[a]	Accident Rate[b]
Deceleration lane	5.83	1,089	186
Exit Ramp	1.48	546	370
Area between speed change lanes	11.87	1,982	167
Entrance Ramp	1.61	1,159	719
Acceleration lane	8.40	1,461	174
Acceleration - deceleration lane	2.45	555	227
Total	31.84	6,792	214[c]

[a]No. of Accidents.
[b]Accidents per 100 Million Vehicle-Miles.
[c]Average Accident Rate.

Oppenlander and Dawson (1970) reviewed available literature and reported a number of findings for merge areas, diverge areas, and weaving areas (*11*):

Merging Area:

- 52 percent of on-ramp accidents occur in the merging area.
- A previous study of 412 on-ramps in Texas reports that 90% of merging accidents are rear-end when the merge area is short.
- As the ratio of ramp to mainline volume increases, the accident rate in the merging area increases, regardless of the length of speed change lanes. When merging traffic is less than 6 percent of the freeway traffic, longer acceleration lanes are of little benefit.
- Entrance terminals where through lanes are on downgrades have a lower accident rate than when mainline traffic is on an upgrade, the top of a crest curve, or the bottom of a sag curve.
- Acceleration lanes in excess of 800 ft improve safety (Exhibit 5-24).
- No relationship has been found between merging angle and safety.

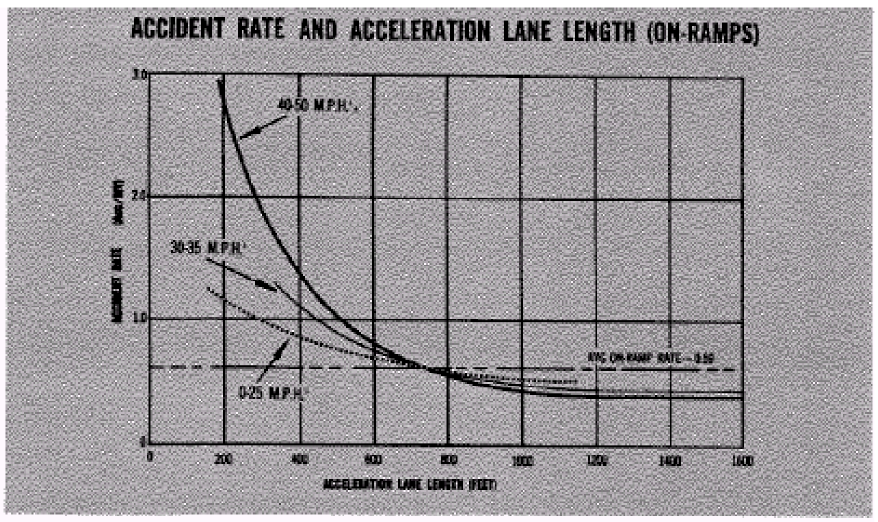
Diverging Area:

- Approximately 44 percent of accidents on off-ramps occur in the exit terminal, and of these over half are single-vehicle accidents
- Deceleration lanes in excess of 800 to 900 feet reduce accident rates by eliminating speed reductions on the through lanes (Exhibit 5-25).
- When the diverging traffic is less than 6 percent no safety benefit is seen by increasing the length of the deceleration lane.
- Geometric designs which hide the gore area from the driver's view pose a risk to drivers.

Weaving Area:

- Accident rates in weaving areas increase for weaving lengths under 700 to 800 ft (Exhibit 5-26).

Exhibit 5-24: Accident Rate and Acceleration Lane Length (on-ramps) (Figure 3 of (11)



[1] Entering Speed at the ramp nose.

Exhibit 5-25: Accident Rate and Deceleration Lane Length (off-ramps) (Figure 5 of (11))

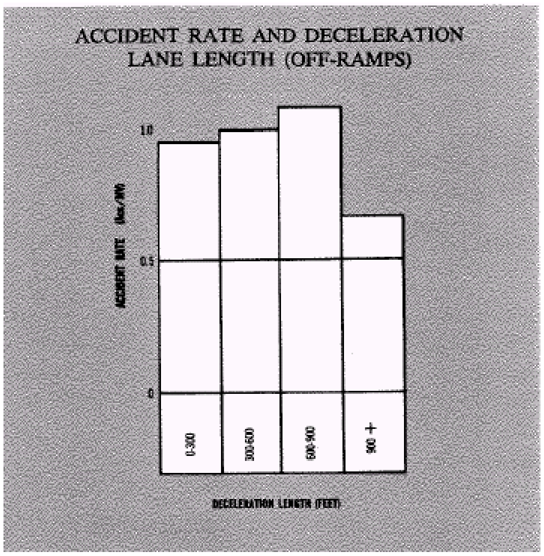
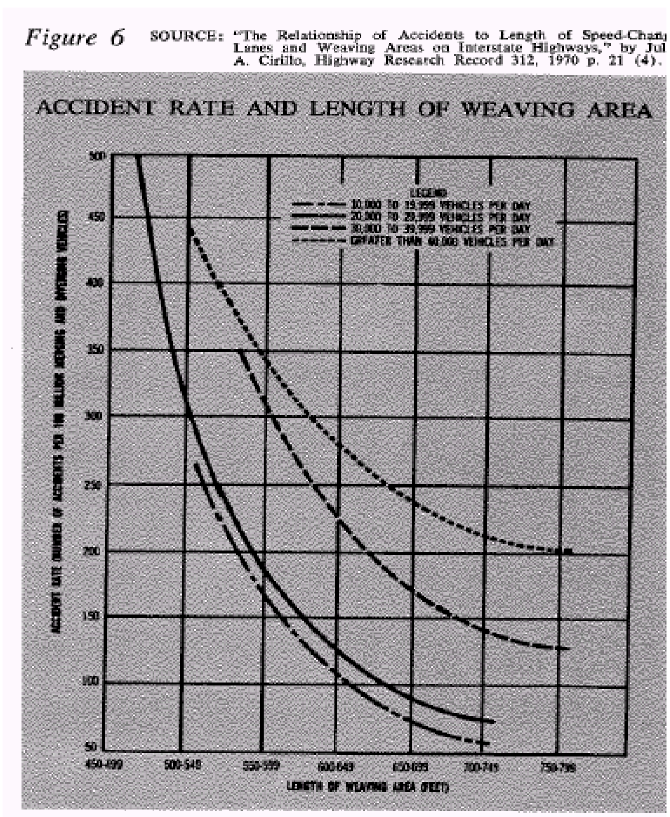


Exhibit 5-26: Accident Rate and Length of Weaving Area (Figure 6 of (11))



A meta-analysis by Elvik and Vaa of three U.S. studies (Lundy 1967; Cirillo 1968, 1970; Yates 1970) and one international study (Wold 1995), shows that increasing the length of an acceleration lane by about 98 ft (30 m) decreases accidents of all types and severities as shown in Exhibit 5-27.(2) Increasing the length of a deceleration lane by about 98 ft (30 m) could decrease accidents of all types and severities as shown in Exhibit 5-27.(2)

Exhibit 5-27: Safety effects of extending speed change lanes (2)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Extend acceleration lane by approx. 98 ft (30 m)	Unspecified	Unspecified	All types All severities	0.89	0.05
Elvik and Vaa, 2004	Extend deceleration lane by approx. 98 ft (30 m)	Unspecified	Unspecified	All types All severities	0.93	0.06

In the FHWA interchange safety analysis tool (*22*), AMF functions for acceleration lane length have been incorporated as follows:

For total accidents (all severity levels combined):

$$AMF = 1.296 * e^{(-2.59 * L_{accel})}$$

For fatal and injury accidents:

$$AMF = 1.576 * e^{(-4.55 * L_{accel})}$$

Where,

L_{accel} = Length of acceleration lane (mi)

L_{accel} is measured from the nose of the gore area to the end of the lane drop taper.

Sarhan et al. (2006) developed negative binomial regression models to relate crash frequency in the interchange area of freeways that included the speed change lanes at the two ends (*20*). Data from 26 interchange along Highway 417 within the city of Ottawa, Ontario, Canada, and between IC 145 West (intersection with Highway 7) and IC 110 East (intersection with Walkley road), were selected for the study. To distinguish between the cases where an acceleration or deceleration lane has unlimited length and is extended to the next ramp, a binary variable was included to indicate if it is an extended lane. The analysis included crash data for a five year period from 1998 to 2002. Two separate models were estimated; one that included length of acceleration lanes as an independent variable and other that included length of deceleration lanes as an independent variable. Similar to many of the negative binomial regression models estimated by other studies, the relationship between crash frequency and the independent variables was assumed to be log-linear. Equation 5-3 shows the forms that were used for the two regression models.

Equation 5-4: Negative binomial regression model form for accidents in interchange areas (20)

$$y = \exp(\beta_0 + \beta_1 EXPO + \sum \beta_i x_i)$$

where, y is the collision frequency, β_i are regression coefficients, x_i are model predictors, and EXPO represents the total traffic exposure for a specific segment in units of million vehicle-km as follows:

$$EXPO = (5\ years)(AADT)(365)(Lseg)(10^{-6})$$

Equation 5-3 shows the regression model that included the length of the acceleration lane.

Equation 5-5: Negative binomial regression model that included length of acceleration lane (20)

$$y = \exp(2.5389 + 0.0168 * EXPO - 0.0020 * LAcc + 1.6269 * AccCo)$$

where, LAcc is the length of the acceleration lane in meters, and AccCo is an indicator variable that was coded as 1 if the acceleration lane was extended, and 0 otherwise.

Equation 5-3 shows the regression model that was estimated for sites with deceleration lanes.

Equation 5-6: Negative binomial regression model that included length of deceleration lane (20)

$$y = \exp(2.7238 + 0.0136 * EXPO - 0.0015 * LDec + 1.2143 * DecCo)$$

where, LDec is the length of the deceleration lane in meters, and DecCo is an indicator variable that was coded as 1 if the deceleration lane was extended, and 0 otherwise. The authors suggest that for sections with both an acceleration lane and a deceleration lane, the average of the expected values from the two models would be the best estimate for the expected number of crashes on that segment.

Based on these models, the AMF for increasing the length of the acceleration lane by 30 meters will be exp(-0.0020*30) = 0.942. Similarly, the AMF for increasing the length of the deceleration lane by 30 meters will be exp(-0.0015*30) = 0.956. These AMFs are not proposed for the HSM because they are derived from the cross sectional models. The AMFs from Elvik and Vaa (*2*) (Exhibit 5-27) based on a meta-analysis of results from several studies is more defensible and proposed for the HSM.

Increasing the right shoulder width of deceleration or acceleration lanes appears to increase accidents.(*5*) However, the safety effect is not certain at this time.

Treatment: Modify two-lane-change merge/diverge area to one-lane-change

Elvik and Erke reviewed additional international literature to update the "Handbook of Road Safety Measures". The findings of their update meta-analysis were considered medium high, and a MCF of 1.8 was assigned to the standard errors reported, as shown in Exhibit 5-28.(*9*)

Exhibit 5-28: Safety effects of modifying two-lane-change merge/diverge area to one-lane-change (9)

Author, date	Treatment	Setting Interchange type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Erke, 2007	Modify two-lane to one-lane merge/ diverge area	Unspecified	Unspecified	Accidents in the merging lane, All severities	0.68	0.04

NOTE: Based on U.S. studies: Lundy 1967; Cirillo 1968, 1970; Yates 1970; Bauer, Harwood 1998; Janson et al. 1998; Bared, Giering & Warren 1999; Khorashadi 1998; Golob, Recker & Alvarez 2004; McCartt et al. 2004; Lee et al. 2002 and International studies: Wold 1995; Pajunen 1999; Tielaito 2000.

Discussion: Angle of convergence

Leisch et al. cite several studies of the safety effects of various angles of convergence of interchange ramps. Although no AMFs or safety data are provided, the operational characteristics of lower angles of convergence appear to be more desirable than the operational characteristics of higher angles of convergence. Specifically, "smooth flow" was found at merges with an angle of convergence of 3 degrees or less. Driver gap acceptance was higher at small convergence angles, which Leisch et al. relate to smoother traffic flow, less stopping, and a reduced likelihood of rear-end collisions.(*8*)

5.1.3. Ramp Roadways

As defined in Chapter 25 of the Highway Capacity Manual "a ramp is a length of roadway providing an exclusive connection between two highway facilities. The facilities connected by a ramp may consist of freeways, multilane highways, two-lane highways, suburban streets, and urban streets. A ramp may consist of up to three geometric elements of interest: ramp-freeway junction, ramp roadway, ramp-street junction." (*10*). Note that the Highway Capacity Manual (2000) considers ramp-freeway junction and ramp roadway collectively for capacity analysis.

This section discusses the accident experience of interchange ramp roadways. Discussion of HOV lanes on entrance or exit ramps will be included in Chapter 6.

Exhibit 5-29: Resources examined to investigate the safety effect of ramp roadway elements at interchanges

DOCUMENT	DESCRIPTION	COMMENT
(*16*)(Parajuli, B., Persaud, B., Lyon, C., and Munro, J., "Safety Performance Assessment of Freeway Interchanges, Ramps, and Ramp Terminals", Presented at the Road Safety Engineering Management Section of the 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island, (2006))	Negative binomial regression models were estimated for different categories of ramps.	Added to synthesis.
(*21*)(Lord, D. and Bonneson, J.A., "Calibration of Predictive Models for Estimating Safety of Ramp Design Configurations", Transportation Research Record 1908, pp. 88-95, (2005))	Recalibrated the models developed by Bauer and Harwood (1998) for 44 ramps in Texas.	Added to synthesis.
(*2*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Added to synthesis.
(*12*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Crashes." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Synthesis of strategies to reduce aggressive driving crashes.	Discussion of short ramp length and aggressive driving added to synthesis. No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
(Bahar, G., DiLorenzo, T., Munro, J., and Persaud, B., "Prioritization of Interchanges and Ramps based on Potential for Safety Improvements." Monterey, Calif., Institute of Transportation Engineers Spring Conference and Exhibit, (2001))	Developed SPFs for interchanges and ramps in Ontario.	No AMFs. Not added to synthesis.
(Janson, B., Kononov, J., Awad, W., Robles, J., and Pinkerton, B., "Effects of Geometric Characteristics of Interchanges on Truck Safety." CDOT-DTD-R-99-3, Denver, Colorado Department of Transportation, (1999))	Used crash data from WA, CO, and CA to identify relationships between truck accidents and geometric characteristics of interchanges including merge/diverge areas.	Not added to synthesis.
(Khorashadi, A., "Effect of Ramp Type and Geometry on Accidents." FHWA/CA/TE-98/13, Sacramento, California Department of Transportation, (1998))	Accident rates were analyzed to assess the differences between ramps.	Suggested by NCHRP 17-18(4). This study deals with ramp configuration, not ramp design. Not added to this section.
(*5*) (Bauer, K. M. and Harwood, D. W., "Statistical Models of Accidents on Interchange Ramps and Speed-Change Lanes." FHWA-RD-97-106, McLean, Va., Federal Highway Administration, (1997))	Developed negative binomial regression models for accidents on interchange ramps and speed change lanes.	Suggested by NCHRP 17-18(4). Added to synthesis.
(*7*) (Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." Transportation Research Record 1383, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.)	Reviewed past research that studied the effect of interchange design and accidents including acceleration and deceleration lanes.	Suggested by NCHRP 17-18(4). Added to synthesis.
(Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume IV - Interchanges." FHWA-RD-91-047, Washington, D.C., Federal Highway Administration, (1992))	Reviewed past research that studied the effect of ramp design on safety.	Suggested by NCHRP 17-18(4). Same material as for Twomey et al. (1993), not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Old document, any relevant material would likely have been covered in Twomey (1992).	Not added to synthesis.
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))	Old document, any relevant material would likely have been covered in Twomey (1992).	Not added to synthesis.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Summarized in Various 1982	Not added to synthesis.
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	No information on ramp geometry.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Slatterly Jr., G. T. and Cleveland, D. E., "Traffic Volume." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 2, Washington, D.C., Automotive Safety Foundation, (1969))	Old document, any relevant material would likely have been covered in Twomey (1992).	Not added to synthesis.

Discussion: Accident experience of interchange ramp roadways

Bauer and Harwood (1997) developed negative binomial regression models for accidents on interchange ramps and speed change lanes. Data from the State of Washington were used to develop separate models for total and fatal+injury accidents (*5*). The database analyzed included five types of ramp configurations:

1. Diamond
2. Parco loop
3. Free-flow loop
4. Outer connection
5. Direct or semi-connection

The following combinations of elements were successfully modeled:

- Ramp proper segments (off- and on-ramps combined and off-ramps only)
- Entire ramps (off- and on-ramps combined and off-ramps only)
- Acceleration lanes
- Deceleration lanes
- Entire ramps plus adjacent speed-change lanes

Ramp proper segments are sub-segments on a ramp with a constant cross-section. These ramp proper segments were defined in an attempt to relate accident frequency to cross-section geometrics. Entire ramps include whole ramps from the entry/exit gore to the exit terminal/merge gore.

The best explanatory variable for all models was the ramp Annual Average Daily Traffic (AADT). Other significant variables in some models included mainline AADT, rural/urban location, ramp type (on/off), ramp configuration, and length of ramp + speed-change lane. Other variables attempted included travel way width for ramps and speed-change lanes, right shoulder width for ramps and speed-change lanes, left-shoulder width for ramps, ramp grade (upgrade/downgrade), and radii of horizontal curves on ramps.

Exhibit 5-30 shows the estimated parameter values, their 90% confidence intervals, and the relative effects of each variable included in the final models. The model form used is shown in Equation 5-7.

Equation 5-7: Negative binomial regression model form for accidents on interchange ramps and speed change lanes (5)

$$\text{Accident frequency} = \text{alpha}(AADT)^{b0}\exp(b_1X_1+b_2X_2+\ldots+b_nX_n))$$

where alpha and $b_0 \ldots b_n$ are the estimated parameters.

The relative effect indicates the expected change in accident frequency for a unit change in that variable. Only those variables related to interchange type are reported in Exhibit 5-30. All models included terms for AADT so exposure has been controlled for. The estimates are not shown here for the AADT terms.

These relative effects are not intended for use as AMFs; as noted by the original authors: "The models presented here, which focus on expected values, are not intended to predict which specific ramps will have extremely high accident frequencies". Rather, these models may be calibrated by agencies for predicting the safety performance of ramps of various types. Nevertheless, based on the models, the following trends are noted (*5*):

- Results for ramp proper, entire ramps, and entire ramps and speed change lanes combined, indicate that off-ramps have a higher accident frequency than on-ramps.
- For AADT from 27 veh/day to 24,365 veh/day, ramps with one lane experience fewer accidents than ramps with 2 or more lanes.
- Increases in right shoulder width of 1 ft predict a 7 percent increase in fatal+injury accidents on acceleration lanes.
- Increases in lane width of 1 ft predict a 6 and 8 percent decrease in total and fatal+injury accidents respectively on off-ramps.
- Ramps in rural areas are expected to have a lower accident frequency than urban ramps for both total and fatal+injury accidents. When entire ramps and speed change lanes are modeled together, accidents are higher in rural areas for total accidents but lower in rural areas for fatal+injury accidents.

Exhibit 5-30: Results of Interchange Models developed by (5)

Independent variable [a]	Ramp Area	Total Accidents		F+I Accidents	
		Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]	Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]
Ramp Type Off-ramp On-ramp	Ramp Proper	0.78 (-0.04, 1.61) 0	2.18 (0.96, 5.00) -	1.45 (0.58, 2.32) 0	4.263 (1.786, 10.176) -
	Entire Ramps	0.50 (0.31, 0.70) 0	1.649 (1.363, 2.014) -	0.55 (0.33,0.76) 0	1.733 (1.391, 2.138) -
	Entire Ramp and Speed Change Lane	0.37 (0.16, 0.58) 0	1.448 (1.174, 1.786) -	0.48 (0.25, 0.71) 0	1.616 (1.284, 2.034) -
Number of lanes 1 2 or more	Ramp Proper	0.77 (0.49, 1.05) 0	2.16 (1.632, 2.858) -	0.78 (0.49, 1.06) 0	2.181 (1.632, 2.886) -
	Ramp Proper – Off Ramps Only[b]	1.03 (0.67, 1.39) 0	2.801 (1.954, 4.015) -	1.20 (0.75, 1.67) 0	3.320 (2.117, 5.312) -
Right shoulder width (ft)	Ramp Proper			0.07 (0.02, 0.11)	1.073 (1.020, 1.116)
Average lane width (ft)	Ramp Proper – Off Ramps Only[b]	-0.06 (-0.11, -0.01)	0.942 (0.896, 0.990)	-0.08 (-0.15, -0.02)	0.923 (0.861, 0.980)
Area Type Rural	Entire Ramps	-0.35 (-0.62, -0.07) 0	0.705 (0.538, 0.932) -	-0.34 (-0.66, -0.02) 0	0.712 (0.517, 0.980) -

Independent variable [a]	Ramp Area	Total Accidents		F+I Accidents	
		Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]	Estimate (90% C.I.)[a]	Relative Effect (90% C.I.)[1]
Urban	Entire Ramp and Speed Change Lane	0.37 (0.16, 0.58) 0	1.448 (1.174, 1.786) -	-0.26 (-0.50, -0.02) 0	0.771 (0.606, 0.980) -

NOTES:

a – variables for Entire Ramp and Speed Change Lane are significant at 20% level

b – rear-end accidents and accidents related to cross-road ramp terminal excluded

1 – Relative effect indicates the expected percentage change in accident frequency for a unit change in that variable. These values cannot be used to develop AMFs.

Lord and Bonneson (2005) recalibrated the models developed by Bauer and Harwood (1998) using data from 44 ramps in and around Austin, TX (*21*). The intent was to estimate the safety of several ramp design configurations – diagonal ramps, non-free-flow ramps, free-flow ramps, and outer connection ramps. The results of recalibration indicated that more crashes occur on exit ramps compared to entrance ramps by a ratio of about 6 to 4. In addition, non-free-flow ramps experienced twice as many crashes as other types.

Parajuli et al. (2006) (discussed earlier) estimated negative binomial regression models for 9 categories of ramps (*16*):

- Flared on-ramps (354 sites)
- Loop on-ramps (270 sites)
- Flared and loop combined on-ramps (624 sites)
- Flared off-ramps (413 sites)
- Loop off-ramps (116 sites)
- Flared and loop combined off-ramps (529 sites)
- Freeway-freeway ramps (124 sites)
- Other on-ramps (87 sites)
- Other off-ramps (134 sites)

Equation 5-8 shows the form that was used for the ramp crashes. The models included AADT and length of the ramp in kilometers.

Equation 5-8: Negative binomial regression model form for mainline crashes (16)

$$Collisions / year = a(AADT)^{b} e^{c(length)}$$

Exhibits 5-31 through 5-33 provide the parameter estimates, standard errors, and the number of crashes that were used to estimate these models. Very few crashes were available to estimate the models for other on-ramps and other off-ramps and hence these results should be used with caution. Exhibit 5-34 shows some summary statistics on the ramp volume that was used for the modeling.

Exhibit 5-31: Results of Ramp Models developed for Flared and Loop on-ramps (16)

Crash Type	Variable	Flared on-ramps (354 sites)		Loop on-ramps (270 sites)		Flared and Looped Combined On-Ramps (624 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
Injury and Fatal	ln(a)	-8.9013	0.7744	-8.4405	0.8568	-8.788	0.5826
	b	0.7962	0.0883	0.6741	0.0987	0.7561	0.0664
	c	0.0968	0.3422	1.2251	0.413	0.5259	0.291
	φ	0.6617	0.1508	0.2939	0.1522	0.5665	0.1116
PDO	ln(a)	-7.4134	0.5149	-6.0394	0.492	-6.8203	0.3589
	b	0.7535	0.0579	0.563	0.0573	0.6717	0.041
	c	0.9483	0.3487	1.3569	0.3201	1.1316	0.2386
	φ	0.8262	0.092	0.4623	0.075	0.6863	0.0611
Crash counts	Injury/Fatal	311		180		491	
	PDO	1,408		824		2,232	

Exhibit 5-32: Results of Ramp Models developed for Flared and Loop off-ramps (16)

Crash Type	Variable	Flared off-ramps (413 sites)		Loop off-ramps (116 sites)		Flared and Looped Combined Off-Ramps (529 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
Injury and Fatal	ln(a)	-9.1476	0.591	-8.3723	1.2133	-8.9626	0.5258
	b	0.851	0.0662	0.7002	0.1425	0.8148	0.0592
	c	0.3564	0.3206	1.4753	0.7227	0.6489	0.3036
	φ	0.6073	0.1034	1.2532	0.3874	0.7158	0.1058
PDO	ln(a)	-8.0417	0.3645	-8.1072	0.7905	-8.0689	0.3306
	b	0.8911	0.0415	0.8478	0.0932	0.8847	0.0037
	c	0.198	0.1877	0.9718	0.5124	0.3426	0.187
	φ	0.3796	0.043	0.6811	0.1427	0.4357	0.0431
Crash counts	Injury/Fatal	645		130		775	
	PDO	2,645		503		3,148	

Exhibit 5-33: Results of Ramp Models developed for Freeway to Freeway and Other Ramp Types (16)

Crash Type	Variable	Freeway-Freeway Ramps (124 sites)		Other on-ramps (87 sites)		Other off-ramps (134 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
Injury and Fatal	ln(a)	-8.3446	0.9828	-12.8018	3.5616	-10.5913	2.1429
	b	0.7742	0.1055	1.0653	0.4019	0.8505	0.2453
	c	0.4447	0.2457	0.9403	4.7567	2.5585	4.7026
	φ	0.9077	0.1872	2.6718	2.1477	1.9855	1.04

Crash Type	Variable	Freeway-Freeway Ramps (124 sites)		Other on-ramps (87 sites)		Other off-ramps (134 sites)	
PDO	ln(a)	-7.8696	0.7589	-6.5062	1.142	-8.7222	1.259
	b	0.8694	0.082	0.4832	0.1376	0.7763	0.144
	c	0.5529	0.2129	4.9637	2.4673	5.1396	2.9624
	φ	0.7466	0.111	1.489	0.5102	1.403	0.365
Crash counts	Injury/Fatal	409		15		37	
	PDO	1,725		86		169	

Exhibit 5-34: Summary of Ramp Volume Data for Modeling (16)

Ramp Type	**Mean AADT**	**Minimum AADT**	**Maximum AADT**
Flared	6,199	63	62,842
Loop	4,787	40	33,543
Freeway to Freeway	12,170	320	43,692
Flared and Loop	5,728	40	62,842
Othres	4,368	13	24,934

Exhibits 5-35 and 5-36 are graphs showing the relationship between AADT and crash frequency for selected ramp types. These were derived from the models shown in exhibits 5-31 through 5-33. Consistent with results from previous studies, off ramps (within a particular category) seem to experience more crashes compared to on-ramps. For fatal and injury crashes, loop off ramps have the highest frequency, while for PDO crashes, freeway to freeway ramps have the highest frequency. Again, it should be emphasized that the models estimated in Parajuli et al. are meant to be predictive rather than causal models, and hence results regarding the safety effectiveness of ramp types based on these models should not be considered definitive.

Exhibit 5-35: Relationship between frequency of injury and fatal crashes and AADT for different ramp types (derived from Parajuli et al (16))

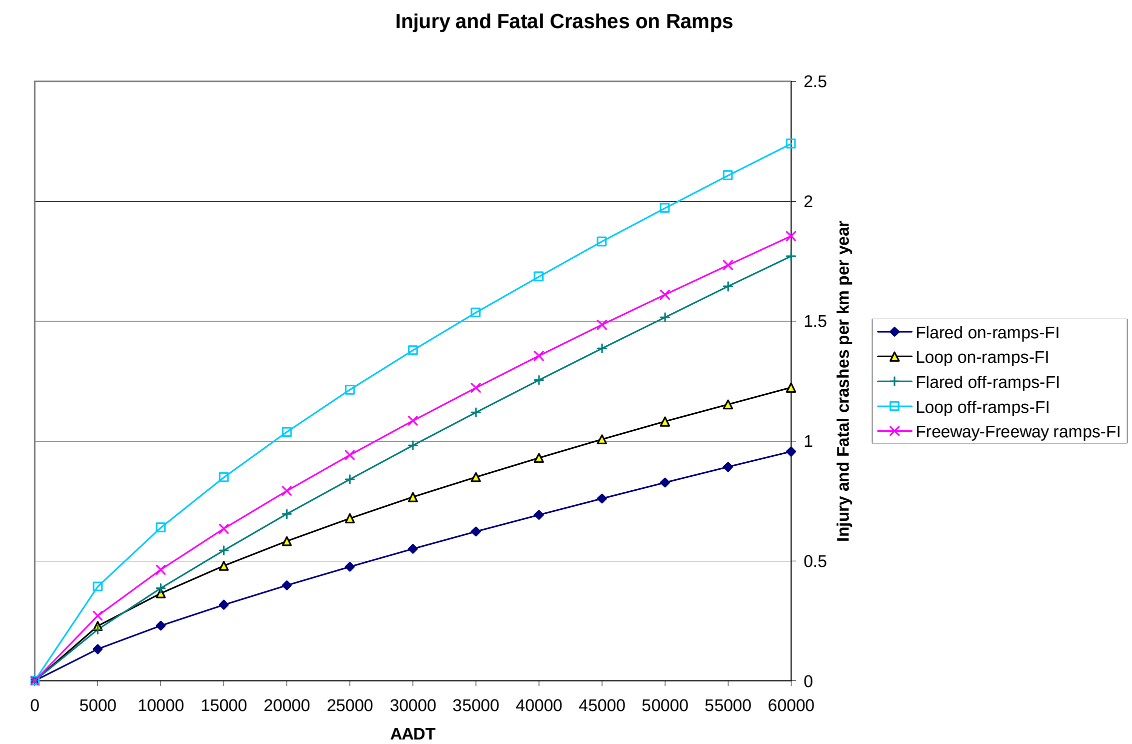
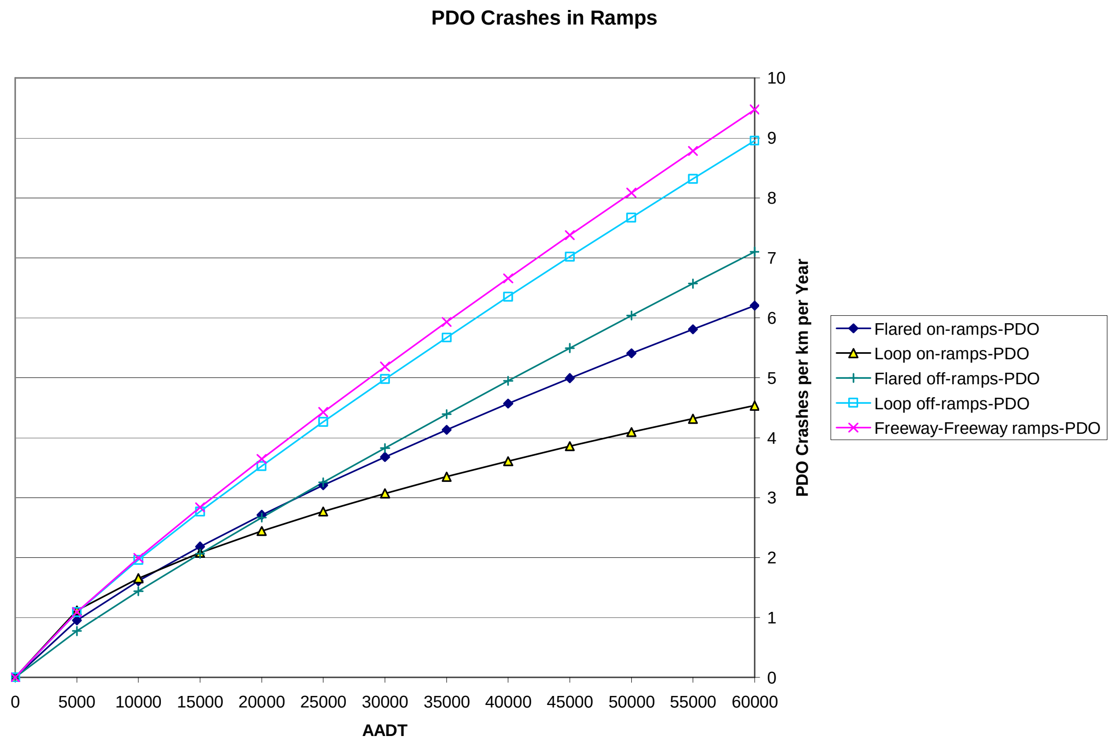


Exhibit 5-36: Relationship betweenPDO crashes and AADT for different ramp types (derived from Parajuli et al (16))



Twomey et al. (1993) reviewed literature dealing with the safety of interchange features (*7*). The findings illustrated in Exhibit 5-37 to Exhibit 5-39 are relevant to horizontal and vertical curvature on ramps; in summary:

- With the exception of loop ramps in rural areas, all right-side and outer-connection loops show an increase in accident rate with increasing maximum curvature.
- Straight outer-connections have lower accident rates than curved connections in both urban and rural areas and for all ADT levels, except 0 to 499 ADT in urban areas.
- Rural loops have higher accident rates with lower curvature, while urban loops have higher accident rates at higher curvature.
- Off-ramps have higher accident rates than on-ramps.
- Grade has no effect on on-ramp accidents but downhill off-ramps have a higher accident rate than uphill off-ramps.
- Ramps should be designed with flat horizontal curves except in rural areas.
- Sharp curves at the end of ramps and sudden changes from straight to sharp curves should be avoided.

Exhibit 5-37: Accident Rates on Outer Connections by Curvature and ADT (Table 1 from (7))

ADT	Urban[a]		Rural[a]	
	Straight <1°[b]	Curved >1°[c]	Straight <1°[b]	Curved >1°[c]
0-499	0.74	0.64	0.00	0.67
500-1000	0.34	0.72	0.13	0.49
1001-1500	0.64	0.64	0.00	0.61
1501-2000	0.15	0.93	0.00[d]	0.20
>2001	0.49	0.82	0.00[d]	0.72
all volumes	0.44	0.81	0.05	0.56

[a] Accidents per 100 million vehicles.
[b] Less than 1 degree of curvature.
[c] Greater than 1 degree of curvature.
[d] Less than 10 units.

Exhibit 5-38: Accident Rates on Loops by Curvature and ADT (Table 2 from (7))

ADT	Urban		Rural	
	Low[a] <12°[b]	High[a] >36°[c]	Low[a] <12°[b]	High[a] >36°[c]
0-499	0.000[d]	0.841	1.000	0.26
500-1000	0.000[d]	0.960	0.810	0.37
1001-1500	1.320[d]	0.890	0.000[d]	0.00
1501-2000	0.000[d]	0.720	0.000[d]	0.00
>2001	0.141	1.000	0.000[d]	0.00
all volumes	0.200	0.940	0.631	0.25

[a] Accidents per 100 million vehicles.
[b] Less than 12 degrees of curvature.
[c] Greater than 36 degrees of curvature.
[d] Less than 10 units.

Exhibit 5-39: Accident Rates by Ramp Type and Curvature (Table 3 from (7))

TABLE 3 Accident Rates by Ramp Type and Curvature

Ramp	No. Ramps	No.[a] Accidents	MV[b]	Accident Rate[c]
On-ramps Straight	180	282	524.5	0.54
Curved	150	229	335.2	0.68
Off-ramps Straight	188	420	536.0	0.78
Curved	142	258	310.1	0.81
Total on & off Straight	368	702	1060.5	0.66
Curved	292	487	645.3	0.75

[a] No. of Accidents
[b] Million Vehicles.
[c] Accidents per Million Vehicles.

NCHRP Report 500 Volume 1 notes that the lack of adequate exit ramp length encourages aggressive driving as manifested by shoulder or median driving (*12*). The lack of adequate entrance ramp length is cited as encouraging improper merging behavior.

Discussion: Increase horizontal curve radius of ramp roadway

Increasing the horizontal curve radius of a ramp roadway appears to decrease accidents of all types and severities. Elvik and Vaa provide an AMF of 0.77, and a 95% confidence interval of 0.72 to 0.83.(2) However, the baseline condition of the horizontal curve and the amount of change to the radius is not clear.

Discussion: Increase lane width of ramp roadway

Increasing lane width on off-ramps appears to decrease accidents. However, the baseline condition of lane width and the amount of widening is not clear.(*5*)

Discussion: Increase shoulder width of ramp roadway

Increasing shoulder width on acceleration lanes appears to increase injury accidents. However, the baseline condition of shoulder width and the amount of widening is not clear.*(5)*

Treatment: Modify ramp type or configuration

Elvik and Erke reviewed additional international literature to update the "Handbook of Road Safety Measures". The findings of their update meta-analysis were considered medium high, and a MCF of 1.8 was assigned to the standard errors reported, as shown in Exhibit 5-40.

Exhibit 5-40: Safety effects of modifying ramp type or configuration (9)

Author, date	Treatment	Setting Interchange type	Traffic Volume	Accident type Severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Erke, 2007	Provide long ramp instead of shortramp[1]	Unspecified	Unspecified	Accidents on the ramp, All severities	0.62	0.1
Elvik and Erke, 2007	Provide straight ramp instead of cloverleaf ramp				0.55	0.2
Elvik and Erke, 2007	Provide cloverleaf ramp instead of long ramp[1]				0.77	0.2
Elvik and Erke, 2007	Provide short ramp instead of directional loop ramp[1]				0.70	0.2

NOTE: Based on U.S. studies: Lundy 1967; Cirillo 1968, 1970; Yates 1970; Bauer, Harwood 1998; Janson et al. 1998; Bared, Giering & Warren 1999; Khorashadi 1998; Golob, Recker & Alvarez 2004; McCartt et al. 2004; Lee et al. 2002 and International studies: Wold 1995; Pajunen 1999; Tielaito 2000.
1) Definitions of short and long ramps were not specified

Interchange configuration includes many design elements. The following general guidance may be considered for interchange design elements:

- Direct/semi-direct connectors appear to have the best safety performance on the ramp proper compared to other configurations for both off-ramps and on-ramps.*(5)*
- Diamond configuration appears to have an adequate safety performance on the ramp proper compared to other configurations for off-ramps, but a poorer safety performance on the ramp proper for on-ramps.*(5)*

- Loop ramps appear to have a poorer safety performance on the ramp proper compared to other configurations for both off-ramps and on-ramps.*(5)*
- Outer connectors appear to have a poorer safety performance on the ramp proper compared to other configurations for off-ramps, but an adequate safety performance on the ramp proper for on-ramps.*(5)*

Summary

The Bauer et al. models are not useful for deriving AMFs. These models, while not in a counterintuitive direction, are likely to be inaccurate due to the many omitted variables and likely correlations among variables used.

These models, however, are recommended for predicting the safety performance of interchange ramps since these were done with a complete database using the latest modeling techniques. This is a very important application, given that the current edition of the HSM will not contain such models. The models will need to be calibrated in order to apply them in other jurisdictions and time periods using the recalibration procedure presented in Part III. A similar argument could be made for models from Parajuli et al. (*16*) and Sarhan et al. (*20*), which are again predictive (not causal models) and are likely to be at least a bit inaccurate due to the many omitted variables and likely correlations among variables used.

The Twomey et al. summary provides some logical insights, as does that of Neuman et al., but this is all that they provide. That many conclusions are in accord with good design practice (e.g. that long ramps with gentle curvature is good) suggests that the conclusions, though useful, add little to the inherent knowledge base of a good designer.

5.1.4. Ramp Terminals

Interchange ramp terminals are defined by the Highway Capacity Manual (2000) as “a junction with a surface street to serve vehicles entering or exiting a freeway” (plural is “terminals”).

At this time, very little information is available regarding the safety and design of interchange ramp terminal intersections. Chapter 4 contains information on the design and operation of intersections and safety.

Pedestrians and cyclists are discussed in Section 5.3. Ramp terminal traffic control is discussed in Section 5.2.1.

Exhibit 5-41: Resources examined to investigate the safety effect of interchange ramp terminals

DOCUMENT	DESCRIPTION	COMMENT
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing meta-analysis results of safety studies for a variety of topics.	Not added to synthesis.
NCHRP Project 15-31 “Design Guidance for Freeway Mainline Ramp Terminals” CH2MHill	Objective: to develop improved design guidance for freeway mainline ramp terminals, should also address issues related to design of gore area and transitional area to ramp proper.	On-going. Not added to synthesis
(*13*) (Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999))	Limited discussion of ramp terminals	Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*8*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	No AMFs for ramp terminals. Some qualitative knowledge.	Added to synthesis.
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))	No information on ramp terminals	Not added to synthesis.
(Leisch, J. E., "Alinement." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 12, Washington, D.C., Highway Users Federation for Safety and Mobility, (1971))	Summarized in Various 1982	Not added to synthesis.
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))	No information on ramp terminals	Not added to synthesis.

Gluck et al. (1999) cite the AASHTO booklet, “A Policy on Design Standards – Interstate System (July 1991)” that access control on the crossing route should extend beyond the ramp terminal at least 100 ft in urban areas and 300 ft in rural areas (*13*). Gluck et al. also note that where intersections are too close to ramp terminals, heavy weaving volumes and accidents may result. They further note that the spacing between ramp terminals and cross-route access points must allow for proper merging, weaving, and diverging of ramp and arterial traffic. No analysis of accident data is reported.

These guidelines are supported by intuition and not by empirical evidence. As such, though insightful, they should be applied with the same consideration as any guideline that is not scientifically based.

Leisch et al. conclude that the arrangement of ramp terminals, including sequencing, spacing, and location of entrances and exits, is important in the operation and safety of interchanges.(*8*) For example, ramp sequences which create weaving sections, such as cloverleaf interchanges, can reduce the safety performance of an interchange. The spacing of consecutive entrances and exits can impact safety performance if adequate deceleration or acceleration lengths are not provided.(*8*)

5.1.4.1. Acceleration and Deceleration Lanes [Future Edition]

In future editions of the HSM, this section may provide information on the safety effects of acceleration and deceleration lanes to the ramp terminal intersection. Potential resources are listed in Exhibit 5-42.

Exhibit 5-42: Potential resources on the relationship between the design of acceleration and deceleration lanes at ramp terminals and safety

DOCUMENT
(American Association of State Highway and Transportation Officials, "A Policy on Geometric Design of Highways and Streets, 4th ed. Second Printing." Washington, D.C., (2001)) page 692-693
(Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." Transportation Research Record 1383, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.)

DOCUMENT
(Bared, J., Giering, G. L., and Warren, D. L., "Safety Evaluation of Acceleration and Deceleration Lane Lengths." ITE Journal, Vol. 69, No. 6, Washington, D.C., Institute of Transportation Engineers, (1999) pp. 50-54.)
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))

5.1.5. Other Design Elements

Other design elements associated with interchanges are discussed in the following sections.

5.1.5.1. Closely Spaced Intersections [Future Edition]

In future editions of the HSM, this section may provide information on the effect of intersections closely spaced to interchanges on safety, including closely-spaced ramp terminal intersections, and other intersections on the crossroad. Potential resources are listed in Exhibit 5-43.

Exhibit 5-43: Potential resources on the relationship between the design of closely spaced intersections and safety

DOCUMENT
1983 Nordstrom and Stockton report, "Evaluation of Minor Freeway Modifications"

5.1.5.2. Lane Drops [Future Edition]

In future editions of the HSM, this section may provide information on the effect of lane drops at interchanges on safety, including sight distance to the lane drop, and providing an optional lane. No potential resources were identified.

5.1.5.3. Collector-Distributor Roads [Future Edition]

In future editions of the HSM, this section may provide information on the effect of collector-distributor roads on interchange safety. No potential resources were identified.

5.2. Safety Effects of Interchange Traffic Control and Operational Elements

The following sections discuss various traffic control devices and operational schemes employed at interchanges and interchange ramp terminal intersections. Such devices include intersection signalization, ramp metering, signage, delineation, pavement markings and markers.

5.2.1. Traffic Control at Ramp Terminals

Ramp terminals can be signalized, stop-controlled, free-flowing, yield-controlled, or have channelized right-turn movements.

This section is intended to address aspects of intersection traffic control that are unique to ramp terminals. Information on non-ramp terminal intersections is provided in Chapter 4.

Future editions of the HSM may benefit from research efforts underway in Ontario, Canada and the U.S. to model the safety of ramp terminals.

Exhibit 5-44: Resources examined to investigate the safety effect of traffic control at ramp terminals

DOCUMENT	DESCRIPTION	COMMENT
(*16*)(Parajuli, B., Persaud, B., Lyon, C., and Munro, J., "Safety Performance Assessment of Freeway Interchanges, Ramps, and Ramp Terminals", Presented at the Road Safety Engineering Management Section of the 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island, (2006))	Developed negative binomial regression models relating crash frequency (PDO and fatal/injury) at ramp terminals as a function of AADT and presence/absence of slip lanes. Separate models developed for stop and signalized terminals.	Added to synthesis.
(Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Crashes." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Synthesis of strategies to reduce aggressive driving crashes.	No relevant information, not added to synthesis.
(*8*) (Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis of safety research including traffic control at interchanges	Suggested by NCHRP 17-18(4). No information on ramp terminal control. Information to mitigate wrong way movements added to synthesis.
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))	Comprehensive review includes information on traffic control device applications	Suggested by NCHRP 17-18(4). No relevant information, not added to synthesis.

Most of the models of ramp safety tend to exclude accidents occurring at the intersection. One explanation is that safety on the ramp is largely unrelated to the characteristics of the ramp and cross-street intersection. Another explanation is that different jurisdictions may be involved for the ramp and for the cross-street, and data on traffic volumes and accidents at the ramp terminal intersection are difficult to obtain.

Parajuli et al. developed negative binomial regression models relating the frequency of crashes at ramp terminals with traffic volume and a variable to indicate if the approach ramp is split (whether it has a slip lane for right turning traffic) (*16*). For signalized ramp terminals, the regression models took the following form:

Equation 5-9: Negative binomial regression model form for signalized ramp terminals (16)

$$Collisions / year = a(AADTramp)^{b}(AADTcross)^{c}e^{d(split)}$$

For stop controlled ramp terminals, the regression models took the following form:

Equation 5-10: Negative binomial regression model form for stop controlled ramp terminals (16)

$$Collisions / year = a(AADTtotal)^{b} e^{c(split)}$$

where AADTcross is the sum of approach volumes from two approaches of the side road, AADTramp is the sum of approach volumes from ramp and the service roads, AADTtotal is the total AADT approach the terminal from all approaches, and 'split' is an indicator variable taking the value of zero if the approach ramp is non-split and 1 if the approach ramp is split (i.e., with a slip lane for right turning traffic).

Exhibit 5-45 shows the parameter estimates and standard errors from the models including the negative binomial overdispersion parameter (φ). Exhibit 5-46 shows summary statistics on the ramp volumes used in the analysis. As expected, the models seem to indicate that crashes increase with increase in traffic volume. In addition, ramp terminals with a slip lane for right turning vehicles seems to be associated with fewer crashes – the slip lanes seems more effective in 4 leg signalized intersections compared to the other types. It should be emphasized that the models developed by Parajuli et al. were intended to be used as predictive models (safety performance functions) rather than causal models from which AMFs could be derived. Hence, findings discussed above regarding the possible benefits of slip lanes for right turning vehicles should not be considered definitive.

Exhibit 5-45: Parameter Estimates of Ramp Terminal Regression Models (16)

Collision Type	Parameter	3-leg signalized (140 sites)		4 leg signalized (23 sites)		3-leg and 4-leg stop controlled (144 sites)	
		Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
Injury and Fatal	ln(a)	-12.7762	1.9129	-17.1286	3.9417	-6.9588	1.9920
	b	0.6187	0.1776	0.7150	0.2558	0.5028	0.2077
	c	0.6114	0.1946	0.9685	0.4299	-1.1066	0.3405
	d	-0.7555	0.1478	-2.4316	1.0432		
	φ	0.8132	0.1072	0.1501	0.1235	1.1730	0.4364
PDO	ln(a)	-11.5143	1.3120	-14.4269	4.1520	-6.7506	1.2659
	b	0.7360	0.1123	0.9566	0.2382	0.6087	0.1319
	c	0.5351	0.1181	0.6219	0.4321	-1.0104	0.1976
	d	-0.7636	0.1465	-1.3896	0.4710		
	φ	0.4257	0.0606	0.3328	0.1418	0.5499	0.1240
Crash Counts	Injury & Fatal	565		120		87	
	PDO	2,669		436		305	

Exhibit 5-46: Ramp Terminal Traffic Volume used in the Modeling (16)

Type of Ramp Terminal	Average Approach AADT		Minimum Approach AADT		Maximum Approach AADT	
	Ramp	Cross Road	Ramp	Cross Road	Ramp	Cross Road
3-leg signalized	13,641	39,972	1,148	7,360	57,590	116,969
4-leg	11,351	37,452	1,971	8,793	34,677	76,431

Type of Ramp Terminal	Average Approach AADT		Minimum Approach AADT		Maximum Approach AADT	
	Ramp	Cross Road	Ramp	Cross Road	Ramp	Cross Road
signalized						
3-leg stop controlled	3,261	13,171	83	283	14,552	65,801
4-leg stop controlled	4,026	10,997	1,394	4,384	11,495	31,756

Discussion: Traffic control elements to mitigate wrong way movements

Several treatments have been applied at various interchanges to mitigate wrong way movements at ramp terminals. Although AMFs are not available, the following treatments in combination appear to provide some safety improvement for various interchange types:(*8*)

- Large pavement arrows
- 24 inch stop bar
- DO NOT ENTER sign
- guide sign
- WRONG WAY sign
- NO RIGHT TURN / NO LEFT TURN signs
- KEEP RIGHT sign

5.2.2. Ramp Metering [Future Edition]

Ramp metering is primarily used for congestion management, and may reduce motor vehicle crashes by reducing sideswipes and reducing rear-end crashes caused by vehicles merging during congested periods. However, if not properly designed and operated, ramp meters may increase the crash risk on the surface crossroads.

In future editions of the HSM, this section will provide information on the safety effect of implementing ramp metering at ramp terminals. This section may address the effect of ramp metering on crash risk at an interchange, including the mainline crash risk, ramp crash risk, and the minor road crash risk. Potential resources are listed in Exhibit 5-47.

Exhibit 5-47: Potential resources on the relationship to ramp metering and safety

DOCUMENT
Abdel-Aty, M. and Gayah, V.V., "Comparison of Two Different Ramp Metering Algorithms for Real-Time Crash Risk Reduction", Presented at the 87th Annual Meeting of the Transportation Research Board", Washington, D.C., January 2008.
Lee, C., Hellinga, B., and Ozbay, K., "Quantifying Effects of Ramp Metering on Freeway Safety", Accident Analysis and Prevention, Vol. 38, pp. 279-288, 2006.
MinnDOT, "Twin Cities Ramp Meter Evaluation - Final Report", 2001
Upchurch and Cleavenger, "Freeway Ramp Metering's Effect on Accidents: Recent Arizona Experience", 1999

DOCUMENT
MinnDOT, "Trunk Highway 169 - Dynamic Ramp Metering Evaluation", 1998
(Jernigan, J. D., "Expected Safety Benefits of Implementing Intelligent Transportation Systems in Virginia: A Synthesis of the Literature." FHWA/VTRC 99-R2, Richmond, Virginia Department of Transportation, (1998))
Piotrowicz, "Ramp Metering Status in North America, 1995
Henry and Meyhan, "Six Year FLOW Evaluation", 1989
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

5.2.3. Signs [Future Edition]

In future editions of the HSM, the safety effects of different types and locations for advance warning and information signs on the mainline for exit ramps at interchanges may be discussed in this section. Overhead signs, roadside signs, with retroreflective materials or illuminated and other guidance signs such as street names or route numbers may be of interest. It may be difficult to separate the safety effect of signing from design elements. This section will add to the information provided in other signage sections of the HSM. No potential resources were identified.

5.2.4. Delineation [Future Edition]

Future editions of the HSM may include information on the safety effects of delineated ramp roadways (e.g., chevrons, post mounted delineators), different pavement markings, and raised pavement markers. Delineation may be discussed for different interchange types and ramp types. This section will add to the information provided in other sections of the HSM on delineation. Potential resources are listed in Exhibit 5-48.

Exhibit 5-48: Potential resources on the relationship of delineation, and pavement markings of interchanges and safety

DOCUMENT
(Smiley, A., "Driver Performance at Interchanges." (2004))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))

5.3. Pedestrian and Bicyclist Safety at Interchanges

At interchange ramp terminals, there may be a requirement for the local agency to ensure the continuity of the facilities for pedestrians and bicyclists. This continuity may not be fully considered by other jurisdictions responsible for freeways and higher level crossing roads. Pedestrians are particularly vulnerable to high speed approach vehicles turning at ramp terminals.

No specific AMFs were found in the available literature related to pedestrian and bicyclist treatments at interchanges. Discussion of bicyclists on freeways and at ramp terminals is provided based on limited literature sources. Behavioral studies of pedestrian safety at interchanges are also discussed.

In future editions of the HSM, this section may include quantitative knowledge related to pedestrian and bicyclist safety at interchanges, particularly at ramp terminals. The following treatments may be included: traffic and pedestrian signals, refuge islands, traffic control devices, and specific policies related to pedestrian and bicyclist activity within these areas.

This section will only address aspects of pedestrian and cyclist safety on segments and at intersections that are unique to ramp terminals. Chapter 3 contains related information on these road users on roadway segments. Chapter 4 contains other related information on these road users at intersections.

Exhibit 5-49: Resources examined to investigate the safety of pedestrians and bicyclists at interchanges

DOCUMENT	DESCRIPTION	COMMENT
(*14*) (Ferrara, T. C. and Gibby, A. R., "Statewide Study of Bicycles and Pedestrians on Freeways, Expressways, Toll Bridges and Tunnels." FHWA/CA/OR-01/20, Sacramento, California Department of Transportation, (2001))	Conducted an analysis of bicycle and pedestrian accident data, in part to develop procedures for allowing bicyclists to cross ramps.	Suggested by NCHRP 17-18(4). Added to synthesis.
(Staplin, L., Lococo, K., Byington, S., and Harkey, D., "Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians." FHWA-RD-01-051, Washington, D.C., Federal Highway Administration, (2001))	Several strategies to reduce crashes involving older drivers and pedestrians.	Contained no information specific to pedestrians and cyclists at interchanges. Not added to synthesis.
(*15*) (Zeidan, G., Bonneson, J. A., and McCoy, P. T., "Pedestrian Facilities at Interchanges." FHWA-NE-96-P493, Lincoln, University of Nebraska, (1996))	Study to develop design guidelines for pedestrian facilities at interchanges in Nebraska	Added to synthesis.
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))	Comprehensive review includes information on accommodation of pedestrians and bicyclists at interchanges	Suggested by NCHRP 17-18(4). General discussion of pedestrian and bicyclist design features at ramps, with no research or evaluation results. Not added to synthesis.

Discussion: Bicyclists on freeways, ramps, and at junctions

A study by Ferrara and Gibby in 2001 for the California Department of Transportation (Caltrans) involved a statewide analysis of bicyclist and pedestrian use and accident data on freeway shoulders, including toll bridges and tunnels (*14*). Caltrans policy permits bicyclist travel on these facilities in the absence of a suitable alternate route. The purpose of the study was to clarify some of the relevant issues and develop guidelines for bicyclist and pedestrian traffic on freeway shoulders, bridges, and tunnels.

In 1999, Caltrans officials met with members of bicycle advocacy groups and the California Highway Patrol to discuss the proposed study and develop a list of issues to be addressed. One of the questions was, “What special factors for bicyclist/pedestrian safety are there through interchanges and on/off-ramps?”. The Caltrans study consisted of several parts(*14*):

- A survey of other DOTs;
- A literature review;
- A study of bicyclist-related crashes on freeways in Caltrans Districts 1, 2, and 3, using data from the Traffic Accident Surveillance Analysis System (TASAS) and actual traffic accident reports;
- A study of pedestrian crashes on freeways in Districts 2 and 3, also based on data from TASAS and traffic accident reports;
- An Internet survey of 1,239 bicyclists;
- Analysis of the accident history of certain bridges and tunnels; and
- A statistical analysis of all crashes on freeways, using the independent variable of Bicycle Status (permitted vs. prohibited) to predict accident rates.

From 1990 to 1998, 41 pedestrian and bicyclist crashes on freeways were included in the study, with bicycle-motor vehicle accidents accounting for 61% of the total (25 out of 41). Fourteen of the twenty-five bicycle-motor vehicle crashes occurred at a ramp terminal (10 at off-ramps and 4 at on-ramps (*14*)).

The literature review by Ferrara et al. cited another project that examined Caltrans records for bicycle-motor vehicle crashes from 1988 to 1997 (California Department of Transportation, no date). The records showed that 2,739 bicycle-motor vehicle crashes had been reported on California freeways during that time frame, and that many of them occurred near freeway ramp junctions. During the ten-year period, across a 4,100-mile freeway network, only 3 bicyclist fatalities and 15 bike crashes (0.4%) occurred at both non-ramp and non-intersection locations, and 86 bike crashes (3.1% of the total) occurred on freeway shoulders. A total of 2,556 bicycle-motor vehicle crashes (93.7%) occurred at ramps or intersections. It is evident that bicyclists are most vulnerable to motor vehicle traffic at these areas of the freeway system (*14*). Ferrara et al. note that these results are consistent with the 1995 study by Hunter et al., which concluded that intersections, driveways, and other junctions need special consideration when freeways are designed due to the sizable threat that they present for cyclists. Another report cited by Ferrara et al. (Clarke, 1995), suggests that the best option for accommodating cyclists at ramps is to encourage riders to cross at right angles to motor vehicle traffic, and at a point where they have adequate sight distance (*14*).

Ferrara et al. recommended that cyclists using these high-speed roadways should be required to wear a helmet and have a driver’s license. In addition, bicyclist traffic should only be permitted on freeways that have a minimum 8 ft shoulder width. In addition, Ferrara et al. recommended that drain inlets should be modified to reduce challenges for cyclists (*14*).

A formal bicycle-counting program was recommended by Ferrara et al. to facilitate further research into issues related to bike usage of freeway shoulders, bridges, and tunnels. Bicycle traffic statistics are necessary in order to evaluate the effectiveness of various roadway treatments in enhancing bicyclist safety. One challenge mentioned by Ferrara et al. is the fact that so few serious crashes (28% according to one survey) are ever reported (Moritz, 1996), which limits the reliability of police-reported crash data (*14*).

Returning to the issue of safety at interchanges, the authors emphasize that "the responsibility of crossing a freeway ramp safely should rest with the bicyclist" (*14*). However, the report also noted Caltrans' additional requirement to assess all ramps where bicyclists are allowed to cross on the freeway side. Since cyclists must find adequate gaps in order to safely cross a ramp, Ferrara et al. stated that cyclists should be prohibited from using ramps that have a repeated peak hour volume of 500 veh/hr or more. This recommendation is based on the assumption that a cyclist needs a 7-second gap in the ramp traffic stream in order to make a 40 ft crossing from a stopped position (*14*).

The report also recommends that to be safe, bicyclists attempting to cross a freeway ramp require a minimum sight distance of 760 ft in areas where approaching traffic has a 70 mph speed limit. A sight distance of 460 ft is sufficient when the approach speed is 45 mph. The required sight distance must be equal to, or greater than, the speed of oncoming vehicles multiplied by the 7-second gap necessary to make a ramp crossing. However, even adequate sight distance is not enough to counter traffic volumes at some locations which do not allow the 7 seconds or more required for a cyclist to proceed across the ramp (*14*).

Ferrara et al. recommend that prohibitory signs be posted and alternate routes provided for bicyclists at locations that do not meet both traffic volume levels and sight distances criteria. Furthermore, it is recommended that bicyclists should be restricted from using multilane ramp crossings and weave areas (*14*). Ferrara et al. did not evaluate any roadway treatments related to interchanges.

Discussion: Pedestrians on freeways, ramps, and at junctions

For the period between 1990 and 1998, the Caltrans study found that 327 pedestrian crashes occurred on freeways (*14*). Of these, 64.5% involved drivers who had stopped on the freeway and exited their vehicle. Snow and ice were a major factor in 26.3% of the incidents, and 53.2% of the accidents occurred while pedestrians were assisting a disabled vehicle.

Since most pedestrian crashes on freeways involve motorists who exit their cars to perform maintenance (such as installing snow chains), it was evident that drivers need enhanced education concerning the safe procedure for emergency situations on freeways (*14*).

The purpose of a study by Zeidan et al. was to develop design guidelines for pedestrian facilities at interchanges in Nebraska (*15*). The authors refer to a study conducted in 1978 (Knoblauch et al.), which determined that 42% of all pedestrian accidents on freeways occurred at interchanges. This study underscores the importance of design considerations for pedestrians. Factors such as high volumes of through traffic on cross streets, the large number of vehicles turning onto or off of ramps, wide cross sections, and high speeds are mentioned as contributing to the difficulty of negotiating interchange areas on foot. In addition, the configuration of an interchange creates many potential conflict points between pedestrians and motor vehicles (*15*).

The Zeidan study began with a literature review, which revealed only one document presenting information on pedestrian facilities at interchanges. A lack of national design standards was also noted. Supplemental to the literature review, state departments of transportation were surveyed regarding current state-of-the-art practices; 29 state DOT's responded. Roadway designers and well-known experts on pedestrian issues were also interviewed. Results of the literature review, the surveys, and the expert interviews perpetuated field studies of pedestrian behavior with regard to sidewalks and crosswalks at several freeway interchanges in the city of Omaha (*15*).

At three locations that had existing sidewalks on the cross street, pedestrian use of those sidewalks was observed. Sidewalks were being used almost equally at all three interchange sites, which led Zeidan et al. to conclude that sidewalks will be used in developed areas that generate pedestrians. The three locations observed in this study all had development on all four sides of the interchange; if this were not the case, sidewalks would only be required on the side of the cross street that is developed and creating pedestrian traffic (*15*).

At two other interchanges, observations were made of pedestrian behavior in the crosswalks. The pedestrians at one site were mostly local residents; those at the other site were not. At the first site (with mostly local resident pedestrians), it was found that (*15*):

- 90% of the pedestrians used a proper search pattern before entering the crosswalk to cross the ramp, especially when vehicles were approaching from more than one direction;
- 40% were vigilant in continuing to search for traffic while crossing the ramps;
- 81% followed the intended crossing path, which generally had been designed to minimize exposure time to traffic; and
- 78% complied with pedestrian signals, especially when vehicles were present, which suggest higher compliance when pedestrians perceived the need to do so.

Motorist behavior was also observed in terms of whether or not they yielded to pedestrians in crosswalks at the interchanges. Only a very low percentage (10%) of motorists yielded to pedestrians crossing the ramps (*15*).

At the second location, where many non-local pedestrians were headed to a stadium event, pedestrians exhibited extremely cautious behavior. All of the pedestrians observed used a proper search pattern, and more than 90% showed vigilance while crossing the ramp. Pedestrians were more likely (58% vs. 40% when crossing with traffic) to follow the intended path across the ramp when walking in the opposite direction of cars in the adjacent travel lane (*15*).

The study also found that a high percentage of pedestrians comply with pedestrian signals (e.g., WALK/DON'T WALK) at interchange ramps, particularly when vehicle volumes were high. Overall, motorist yielding behavior, particularly on entrance ramps, was very low. The study did not quantify motorist behavior.

Zeidan et al. developed guidelines for designing pedestrian facilities at interchanges, which include the following (*15*):

- Sidewalks "should be provided between the origins and destinations of existing and future pedestrian trips within the interchange" (page 45).
- Grade separated crossings "may be warranted if a benefit-cost analysis justifies their use".
- Various types of regulatory signs are mentioned from the MUTCD as possibly appropriate to direct pedestrians to use crosswalks or sidewalks, warn pedestrians about certain hazards, provide information about traffic signal operation, or to warn drivers about pedestrians ahead.
- Traffic signals with pedestrian signals are mentioned as possible treatments within interchange areas, if warranted.

- Refuge islands may enhance traffic signal operation, and may be used to keep crosswalk lengths from exceeding 75 ft. Refuge islands must meet ADA requirements and also comply with AASHTO design guidelines.
- Pavement edge lines are suggested treatments on interchange ramps to reduce the effective lane width on the ramp, and thereby reduce vehicle speeds.
- Illumination is also mentioned as a potential treatment, if it meets appropriate warrants.

Zeidan et al. also provide specific criteria describing where marked crosswalks should and should not be provided with respect to interchange ramps (*15*).

Zeidan et al. did not formally evaluate any of the countermeasures, and therefore no AMFs were developed or reported related to interchange areas for pedestrians.

Summary

Only two studies were found which provide information on the safety of pedestrians and/or bicyclists relative to interchange areas. In summary, there is a high potential for pedestrian and bicyclist crashes at the intersection of entrance and exit ramps at interchanges due to high-speed vehicles entering and leaving the freeways. Although pedestrians and bicyclists typically use caution at such crossings, motorists have a low yield rate, particularly at entrance ramps. Furthermore, high vehicle speeds, poor sight distance, high traffic volumes, combined with vulnerable pedestrians and cyclists (e.g., children, older pedestrians) can compromise the safety of the crossing environment for both pedestrians and cyclists.

Therefore, there is often a need to provide specific roadway treatments to help enhance pedestrian and cyclist safety. Some of the possible safety enhancements include adding sidewalks, careful use of crosswalks (and crosswalk enhancements), appropriate warning and regulatory signing (for motorists and pedestrians), traffic and pedestrian signals (if warranted), refuge islands, pavement edgelines (to narrow the width of lanes on ramps), and overhead lighting. No specific AMFs were found in the literature related specifically to such treatments for pedestrians and bicyclists at interchanges.

One study also recommended developing specific policies regarding cyclist and pedestrian use of freeways. Recommendations included insuring that freeways have a shoulder width of at least 8 ft, and well-designed drain inlets to reduce potential challenges for cyclists. Improving sight distance for pedestrians and cyclists at ramp crossings was another recommendation, as well as providing safer alternative routes for pedestrians and bicyclists.

5.4. Safety Effects of Other Interchange Elements

This section of the HSM provides information on the safety effects of the various secondary design and operational elements of interchanges. Topics discussed in the following sections include interchange spacing, illumination, transit stop placement, weather issues, and pavement materials.

5.4.1. Interchange Spacing [Future Edition]

In future editions of the HSM, this section may provide information on the safety effect of spacing between interchanges. This section may be related to Section 5.1.2 with respect to the weaving, merge and diverge areas, which are affected by the distance between consecutive interchanges. Auxiliary lanes between closely spaced interchanges will be discussed in this section. Potential resources are listed in Exhibit 5-50.

Exhibit 5-50: Potential resources on the effect of interchange spacing on safety

DOCUMENT
(Pilko, P., Bared, J.G., Edara, P.K., and Kim, T., "Safety Assessment of Interchange Spacing on Urban Freeways – Enhanced Models", Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2007)
(Bared, J. G., Edara, P., Kim, T., "Safety Impact of Interchange Spacing on Urban Freeways", Presented at the 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2006)
(Chiu, M., Robinson, J. B., Boychuk, R., and Smiley, A., "Evaluating the Road Safety Effects of Interchange Spacing: A Multidisciplinary Approach." Ottawa, Ontario, Canada, Transportation Association of Canada (TAC) Annual Conference 2004, (2004))
(Smiley, A., "Driver Performance at Interchanges." (2004))
(Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." Transportation Research Record 1383, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.)
(Twomey, J. M., Heckman, M. L., and Hayward, J. C., "Safety Effectiveness of Highway Design Features: Volume IV - Interchanges." FHWA-RD-91-047, Washington, D.C., Federal Highway Administration, (1992))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
(Oppenlander, J. C. and Dawson, R. F., "Interchanges." Traffic Control and Roadway Elements - Their Relationship to Highway Safety No. 9, Washington, D.C., Highway Users Federation for Safety and Mobility, (1970))

5.4.2. Illumination [Future Edition]

Illumination is discussed for other sites, such as intersections and roadway segments. In future editions of the HSM, this section will add to that information and may describe the safety effect of partial and full illumination of interchanges, including illumination of the ramp terminal intersection. Various types of illumination may be discussed, including high mast. The effect of illumination along the highway may influence the effect of illumination at interchanges. Potential resources are listed in Exhibit 5-51.

Exhibit 5-51: Potential resources on the effect of illumination on interchange safety

DOCUMENT
(Monsere, C.M. and Fischer, E.L., "Safety Effects of Reducing Freeway Illumination for Energy Conservation", Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2008)
(Elvik, R., "Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure." Transportation Research Record 1485, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 112-123.)
(Griffith, M. S., "Comparison of the Safety of Lighting Options on Urban Freeways." Public Roads, Vol. 58, No. 2, McLean,Va., Federal Highway Administration, (1994) pp. 8-15.)
(Keck, M. E., "The Relationship of Fixed and Vehicular Lighting to Accidents." FHWA-SA-91-019, McLean, Va., Federal Highway Administration, (1991))
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))

5.4.3. Transit Stop Placement [Future Edition]

The relationship of transit stops at interchanges and safety may be discussed in this section in future editions of the HSM. Transit stops may be located on ramp roadways or at interchange ramp terminals, and may take the form of large transportation mode transfer points. Potential resources are listed in Exhibit 5-52.

Exhibit 5-52: Potential resources on the effect of transit stop placement on interchange safety

DOCUMENT
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))

5.4.4. Weather Issues [Future Edition]

In a similar manner as presented in other chapters, weather-related safety treatments and the safety impact when installed at interchanges may be discussed in the following sections.

5.4.4.1. Adverse Weather and Low Visibility Systems [Future Edition]

In future editions of the HSM, the safety effect of adverse weather and/or low visibility at or near interchanges may be discussed in this section. This section would build on similar discussions in other chapters. No potential resources were identified.

5.4.4.2. Snow, Slush, and Ice Control [Future Edition]

In future editions of the HSM, this section may address the effect that snow, slush and ice control methods have on interchange safety performance. This section would build on similar discussions in other chapters. No potential resources were identified.

5.4.4.3. Wet Pavement [Future Edition]

In future editions of the HSM, this section may discuss the safety effect of wet weather, and results conditions such as hydroplaning; and the use of high-friction pavements may be of interest here. This section would build on similar discussions in other chapters. No potential resources were identified.

5.4.5. Pavement Materials [Future Edition]

Drivers perform a great number of maneuvering at approaches to interchanges and at the entry ramp areas. The safety impact of different materials for the surface of these areas may be discussed here in future editions of the HSM. This section would build on similar discussions in other chapters. No potential resources were identified.

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1. American Association of State Highway and Transportation Officials, "A Policy on Geometric Design of Highways and Streets, 4th ed. Second Printing." Washington, D.C., (2001)

2. Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004)

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4. Khorashadi, A., "Effect of Ramp Type and Geometry on Accidents." *FHWA/CA/TE-98/13*, Sacramento, California Department of Transportation, (1998)

5. Bauer, K. M. and Harwood, D. W., "Statistical Models of Accidents on Interchange Ramps and Speed-Change Lanes." *FHWA-RD-97-106*, McLean, Va., Federal Highway Administration, (1997)

6. Garber, N. J. and Smith, M. J., "Comparison of the Operational and Safety Characteristics of the Single Point Urban and Diamond Interchanges." *FHWA-VA-97-R6*, Richmond, Virginia Department of Transportation, (1996)

7. Twomey, J. M., Heckman, M. L., Hayward, J. C., and Zuk, R. J., "Accidents and Safety Associated with Interchanges." *Transportation Research Record 1385*, Washington, D.C., Transportation Research Board, National Research Council, (1993) pp. 100-105.

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13. Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999)

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15. Zeidan, G., Bonneson, J. A., and McCoy, P. T., "Pedestrian Facilities at Interchanges." *FHWA-NE-96-P493*, Lincoln, University of Nebraska, (1996).

16. Parajuli, B., Persaud, B., Lyon, C., and Munro, J., "Safety Performance Assessment of Freeway Interchanges, Ramps, and Ramp Terminals", Presented at the *Road Safety Engineering Management Section of the 2006 Annual Conference of the Transportation Association of Canada*, Charlottetown, Prince Edward Island, 2006.

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Chapter 6: Special Facilities and Geometric Situations

Chapter 6. Special Facilities and Geometric Situations

CONTENTS

EXHIBITS

EQUATIONS

6.1. Railroad-Highway Grade Crossings

According to Tustin et al., railroad-highway grade crossings are unique in that they constitute the intersection of two transportation modes, which differ both in the physical characteristics of their rights-of-way and in their operations (*1*). A railroad-highway crossing, like any highway-highway intersection, involves either a separation of grades or a crossing at-grade (*2*). In the past, railroad companies were allowed to build their tracks across streets and roads at-grade primarily to avoid the high capital costs of grade separations (*1*). Initially, safety at railroad grade crossings was not considered to be a key problem but with the growing volumes of traffic on highways and the introduction of faster vehicles both on the road and on the track, the issue of safety has come to the forefront over the last few decades.

The components of a railroad-highway crossing are divided into two categories: the highway and the railroad. The highway component can be further classified into four elements: the driver; vehicle, roadway, and pedestrians (and other vulnerable road users). The railroad component is classified into its two primary elements: the train; and the track. Given the presence of these components, the location where these two different modes of transportation intersect is designed to incorporate the basic needs of both highway vehicles and trains. A grade separated railroad-highway crossing, by its nature, eliminates the conflict points between the two modes of transportation and consequently, can be regarded as a separate type of facility altogether from grade crossings. Through the elimination of the point of intersection between highway and railroad, a grade-separated crossing provides the highest level of crossing safety (*1*). The focus of the HSM is on railroad-highway grade crossings. Grade-separated crossings are not included.

The "Railroad-Highway Grade Crossing Handbook" (*1*) contains further information on the various components that constitute railroad-highway grade crossings.

This section of the HSM provides information on the safety impact of design elements, traffic control devices, and operational characteristics at railroad-highway grade crossings for all road users.

Safety issues related to pedestrians and bicyclists, and the safety effects of other railroad-highway grade crossing elements such as the presence of trucks and transit vehicles in the vicinity of the crossing may be included in future editions of the HSM. Future editions of the HSM may also be able to provide information for different types of railroad-highway grade crossings such as heavy rail, high speed passenger trains, light rail transit, or regional passenger trains, single and multiple tracks.

6.1.1. Safety Effects of Railroad-Highway Grade Crossing Design Elements

According to AASHTO, the geometric design of a railroad-highway grade crossing involves several elements, namely the alignment, profile, sight distance and cross section (*2*). Furthermore, the design of such crossings and the decision on the type of warning device installed there may benefit from simultaneous action, since the appropriate design may vary with the type of warning device used (*2*). For instance, the highway will ideally cross the railroad at or nearly at right-angles for both active and passive railroad-highway grade crossings. The angle of the crossing is perhaps more critical for passive crossings since passive crossings are controlled with only signs and pavement markings (*2*). Similarly, sight distance is a primary consideration particularly for railroad-highway grade crossings without train-activated warning devices because at these crossings, the driver is expected to visually detect the train and be able to determine whether to stop or continue crossing (*2*).

With regards to the horizontal alignment at railroad-highway grade crossings, AASHTO's "Policy on Geometric Design of Highways and Streets" states that wherever practical, crossings are to be avoided if possible on either highway or railroad curves (*2*). Roadway curvature inhibits a driver's view of a crossing ahead, and a driver's attention may be focused on the curve rather than the train. Likewise, railroad curvature may inhibit a driver's view down the tracks from a stopped position at the crossing and on the approach to the crossing.

In terms of the vertical alignment, it is desirable for the intersection of highway and railroad to be as level as possible for the benefit of improved sight distances and acceleration distances, better rideability, and braking (*2*).

Additional information on the various design elements pertaining to railroad-highway grade crossing is available in the "Railroad-Highway Grade Crossing Handbook" (*1*) and AASHTO's "Policy on Geometric Design of Highways and Streets"

This section of the HSM provides information on the safety effects of the various design elements of railroad-highway grade crossings. The adjacent land use and environment (i.e., urban versus rural) heavily influences the presence of pedestrians, bicyclists and familiar/unfamiliar drivers, as well as the overall level of exposure in terms of rail and vehicular traffic. As such, whenever possible, the safety impact of the design elements related to railroad-highway grade crossings are discussed in the context of these different environments. While this edition of the HSM introduces the reader to the individual design elements that play a role in the overall safety of the crossing, future editions may specifically address and quantify the safety impacts of design elements such as horizontal and vertical alignments, sight distances, and proximity of highway-highway intersections and other access points.

Private crossings will not be addressed separately. Pedestrians and bicyclists are discussed in Section 6.1.3.

6.1.1.1. Crossing Design [Future Edition]

To be addressed in future editions.

6.1.1.2. Cross-section Elements [Future Edition]

To be addressed in future editions.

6.1.1.3. Roadside Elements [Future Edition]

To be addressed in future editions.

6.1.1.4. Alignment Elements [Future Edition]

The safety impacts of different vertical and horizontal alignments and their combinations at approaches to railroad-highway grade crossings may be discussed in this section in future editions of the HSM. Potential resources are listed in Exhibit 6-1.

Exhibit 6-1: Potential resources on the alignment of railroad-highway grade crossings and safety

DOCUMENT
(Bowman, B. L., "The Effectiveness of Railroad Constant Warning Time Systems." Transportation Research Record 1114, Washington, D.C., Transportation Research Board, National Research Council, (1987) pp. 111-122.)
(Wooldridge, M. D., Fambro, D. B., Brewer, M. A., Engelbrecht, R. J., Harry, S. R., and Cho, H., "Design Guidelines for At-Grade Intersections Near Highway-Railroad Grade Crossings." FHWA/TX-01/1845-3, Austin, Texas Department of Transportation, (2000))

6.1.1.5. Sight Distance [Future Edition]

In future editions of the HSM, this section may discuss the safety impact of sight distances to the crossing, sight distance to crossing signals, different angles of intersecting tracks and roadways, sight triangles, roadside hardware, and vegetation, at different operating vehicular and train speeds. Potential resources are listed in Exhibit 6-2.

Exhibit 6-2: Potential resources on the sight distance to railroad-highway grade crossings and safety

DOCUMENT
(Bowman, B. L., "The Effectiveness of Railroad Constant Warning Time Systems." Transportation Research Record 1114, Washington, D.C., Transportation Research Board, National Research Council, (1987) pp. 111-122.)
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))
(Richards, H. A. and Bridges, G. S., "Railroad Grade Crossings." Traffic Control and Roadway Elements - Their Relationship to Highway Safety Vol. Revised, No. 1, Washington, D.C., Automotive Safety Foundation, (1968))

6.1.2. Safety Effects of Railroad-Highway Grade Crossing Traffic Control and Operational Elements

According to the MUTCD, traffic control for railroad-highway grade crossings includes signs, signals markings, other warning devices and their supports along highways approaching and at the crossings for the reasonably safe and efficient operation of both rail and highway traffic (*3*). The MUTCD recognizes that a railroad-highway grade crossing “is situated on a right-of-way available for the joint use of highway and railroad traffic” (*3*). Unlike highway-highway intersections where the right-of-way is alternately assigned to opposing traffic streams, at railroad-highway grade crossings, the right-of-way is always given to the train because of the way it operates and the difficulty in trains responding to quick stops and starts due to their sheer mass. Thus, vehicles on the highway approach are required to stop to avoid a crash, while a train approaching a highway-rail grade crossing has no such requirement unless there is a station at the site.

The Federal Uniform Vehicle Code stipulates that traffic control devices utilized at railroad-highway grade crossings may provide at least two notices of the crossing presence – one in advance to the crossing and the other in proximity to the crossing (*4*). These two classifications of traffic control devices are dealt with in this section.

While the Highway Safety Manual focuses on providing users with quantitative evidence of the safety effects of various treatments measured by accident experience, note that little evidence is available for railroad crossings. This is due to the limited data available; vehicle and pedestrian accidents at grade crossings are relatively infrequent, although usually severe in nature (due to the size and mass of the trains involved). That is, it is just as likely to have zero crashes in a given time period due to randomness as due to the traffic engineering treatment (*5*). Subsequently, many researchers have focused on crossing user movements or risky behavior that present a threat of crash with a train without an actual crash occurring.

The following sections discuss the safety impact of advance traffic control and warning alternatives on the approaches to railroad-highway grade crossings, and the traffic control at the crossings themselves.

Additional information on preemption of traffic signals is available from the ITE Recommended Practice "Preemption of Traffic Signals Near Railroad Crossings" (*6*).

6.1.2.1. Signs and Markings

Advance traffic control and warning alternatives for railroad-highway grade crossings typically consist of signs and pavement markings. Other advance control and warning alternatives include flashing light signals, vehicle activated signals, and transverse rumble strips. The MUTCD provides details on the types of advance warning signs and pavement markings for use at railroad-highway grade crossings, including the standards, guidance and options prescribing when these signs and pavement markings are to be used.(*3*) Further details regarding the use of advance warning signs and pavement markings are available in the MUTCD.

The discussion in this section excludes consideration for signals and gates. These topics are discussed in Section 6.1.2.2.

Exhibit 6-3: Resources examined to investigate the safety effect of signs and markings at railroad-highway grade crossings

DOCUMENT	DESCRIPTION	COMMENT
(*14*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing the effects of various road safety measures and treatments using a meta-analytical approach.	Added to synthesis.
(*7*) (Lerner, N. D., Llaneras, R. E., McGee, H. W., and Stephens, D. E., "NCHRP Report 470: Traffic Control Devices for Passive Railroad-Highway Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (2002))	Includes a detailed critical review of research on the effect of traffic control devices at rail-highway grade crossings; Also evaluated traffic control devices.	Reference suggested by NCHRP 17-18(4). Added to synthesis. Provides summary statement about state of the practice. No safety evidence found.
(Korve, H. W., Ogden, B. D., Siques, J. T., Mansel, D. M., Richards, H. A., Gilbert, S., Boni, E., Butchko, M., Stutts, J. C., and Hughes, R. G., "TCRP Report 69: Light Rail Service: Pedestrian and Vehicular Safety." Washington, D.C., Transportation Research Board, National Research Council, (2001))	Presents "before and after" evaluation of the safety effect of pre-signals at highway-rail grade crossings using motorist behavior, not accidents.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Korve, H. W., "NCHRP Synthesis of Highway Practice Report 271: Traffic Signal Operations Near Highway-Rail Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (1999))	Report presents an overview of current practices regarding the operation of traffic signals at intersections located close to highway-rail grade crossings.	Not added to synthesis.
(*8*) (Fambro, D. B., Noyce, D. A., Frieslaar, A. H., and Copeland, L. D., "Enhanced Traffic Control Devices and Railroad Operations for Highway-Railroad Grade Crossings: Third-Year Activities." FHWA/TX-98/1469-3, Austin, Texas Department of Transportation, (1997))	Research evaluated the effectiveness of a vehicle-activated strobe light and supplemental sign enhancements at passive railroad crossings using a before and after study which investigated changes in speed at the crossings, a driver survey and a driver observation study.	Reference suggested by NCHRP 17-18(4). Added to synthesis. Only evidence of improvements to speed and positive changes to driver behavior.

DOCUMENT	DESCRIPTION	COMMENT
(Richards, S. H., Heathington, K. W., and Fambro, D. B., "Evaluation of Constant Warning Times Using Train Predictors at a Grade Crossing with Flashing Light Signals." Transportation Research Record 1254, Washington, D.C., Transportation Research Board, National Research Council, (1990) pp. 60-71.)	Researchers evaluated the effects of train predictors and constant warning time (CWT) on crossing safety and driver response measures (including risky behavior) at a grade crossing with flashing light signals.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Fambro, D. B., Heathington, K. W., and Richards, S. H., "Evaluation of Two Active Traffic Control Devices for Use at Railroad-Highway Grade Crossings." Transportation Research Record 1244, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 52-62.)	Study investigated the effectiveness of two traffic control devices in changing driver behavior using a before-after study approach. The two devices evaluated for potential safety benefits were four-quadrant flashing light signals with overhead strobes and standard highway traffic signals (pre-signals).	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Heathington, K. W., Fambro, D. B., and Richards, S. H., "Field Evaluation of a Four-Quadrant System for Use at Railroad-Highway Grade Crossings." Transportation Research Record 1244, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 39-51.)	Research examined the safety effectiveness of four-quadrant gates through before and after study of driver behavior.	Not added to synthesis.
(Bowman, B. L., "The Effectiveness of Railroad Constant Warning Time Systems." Transportation Research Record 1114, Washington, D.C., Transportation Research Board, National Research Council, (1987) pp. 111-122.)	Study of the effectiveness of railroad constant warning time (CWT) systems in reducing motorist violations and vehicle-train accidents using 5 years of crash data.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Bowman, B. L., McCarthy, K. P., and Hughes, G., "The Safety, Economic and Environmental Consequences of Requiring Stops at Railroad-Highway Crossings." Transportation Research Record 1069, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 117-125.)	Study examined the safety, economic, operational and environmental consequences of requiring hazardous materials transporters, school buses and passenger buses to stop at railroad-highway crossings with active warning devices when the devices are not activated.	Reference suggested by NCHRP 17-18(4). Not added to synthesis, because reference does not provide necessary information to determine t and s values.
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))	The handbook provides general information on highway-rail grade crossings including overview of various traffic control devices.	Not added to synthesis. Nothing found on safety except for accident prediction models but use of those models to develop t values not valid

Based on a critical review of the references identified previously, it appears that the large majority of studies done to date are based on the use of anecdotal or qualitative evidence of improvements to safety at railroad-highway grade crossings. Some studies have focused on the modifications to driver behavior at these types of grade crossings and have concluded that some treatments are promising in terms of improving driver alertness and comprehension. However, none of the studies reviewed by the researchers were able to make conclusions based on accident experience. This view is shared by Lerner et al. who carried out a literature review of previous research studies and concluded that "one of the more striking and disappointing points is how little appears to be known definitively (or is even reasonably well supported) by empirical data on traffic control device effectiveness" (*7*).

Treatment: Install signs and crossbucks at unprotected railroad-highway grade crossings

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Elvik and Vaa conducted a meta-analysis of a number of studies that investigated the safety effect of signs and crossbucks at previously unprotected railroad-highway grade crossings and found that this particular treatment reduces total grade crossing accidents (p. 579) (*14*). The traffic volumes and environment were not provided in the report. The results from the meta-analysis are summarized in Exhibit 6-4. This study was considered to be of medium-high quality and the standard error value is based on the 95% confidence interval provided by Elvik and Vaa, and a method correction factor of 1.8 was applied to account for the study quality.

Exhibit 6-4: Safety effectiveness of signs and crossbucks at railroad-highway grade crossings

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Implementing signs and crossbucks at previously unprotected crossings.	Not specified.	Not specified.	All grade crossing accidents, severity not specified.	0.75	0.18

Discussion: Impact of vehicle-activated strobe light and supplemental signs on vehicle speeds and driver awareness

Fambro et al. (1997) found that the use of a vehicle-activated strobe light and a "LOOK FOR TRAIN AT CROSSING" supplemental sign in addition to the MUTCD W10-1 sign at passive railroad-highway grade crossings resulted in reduced average vehicle speeds in the vicinity of the crossing (*8*). In addition, the researchers concluded that the enhanced sign system appeared to increase driver awareness of the crossing and, on the basis of results from the observation of drivers, also caused some drivers to "approach the passive railroad-highway grade crossing with additional caution" by advanced braking, switching on their high-beam headlights, and crossing the railroad at lower speeds (*8*).

6.1.2.2. Signals and Gates

The "Manual on Uniform Traffic Control Devices for Streets and Highways" (MUTCD) designates two types of traffic control devices that are used to warn road users that a train is approaching a highway-rail grade crossing: 1) passive devices, and 2) active devices (*3*).

Passive traffic control systems typically consist of signs, pavement markings, and grade crossing illumination that identify and direct vehicle operators and pedestrians' attention to the location of a grade crossing. Stand-alone passive devices provide no information to motorists on whether a train is actually approaching. The devices simply notify highway users that they are about to enter an active railroad (or LRT) alignment, that users need to be aware that trains may approach at any time, and permit vehicle operators and pedestrians to take appropriate action (*9*).

On the other hand, active devices rest in an inactive state until a train approaches. When a train is detected (using some form of track circuitry), grade crossing warning devices consisting of some combination of automatic gates, bells or flashing lights activate. Active devices prompt crossing users with an auditory or visual clue that a train is actually approaching the crossing in question, and in some cases such as when gates are lowered, actually prevent crossing users from occupying or traversing the right-of-way. Nevertheless, active warning devices also have limitations in their effectiveness, particularly when there are occurrences such as drivers maneuvering around lowered gates, or attempting to beat the train to the crossing regardless of whether the grade crossing devices are activated or not. Many active grade crossings continue to use train detection technology that activate crossing control devices based on the fastest trains. This means that trains traveling slower than the design speed or stopping on the approach length result in prolonged activation of the railroad-highway warning system (*10*,*11*).

Previous research studies such as those by Hopkins (1981), Berg et al. (1982), and Wilde et al. (1975) suggest that such excessive and variable warning times may have negative impacts of crossing safety and traffic operations (*11*). Richards et al. demonstrated that there is a "clearly identifiable trend" showing that the longer the waiting time, the greater the number of vehicles that crossed while the (active) warning devices were activated (*11*). This finding has been supported by other studies (*10*,*11*,*12*).

Given the location of many railroad-highway grade crossings in urban areas, it is inevitable that many of these crossings are located in close proximity to highway-highway intersections or experience such high volumes of highway traffic that occurrences of vehicle queues extending over grade crossings are a significant concern. Guidance in the MUTCD states that "when a highway-rail grade crossing with a flashing-light signal system is located within 60 m (200 ft) of an intersection or midblock location controlled by a traffic control signal, the traffic control signal should be provided with preemption in accordance with Chapter 8D.07" (*3*). However, a recent research study has reported that there is widespread concern that during the traffic signal preemption sequence, motorists focus on the downstream intersection traffic signal indications instead of focusing on the flashing light signals located at the grade crossing (*5*). Consequently, the use of traffic signals installed on the near side of railroad-highway grade crossings located adjacent to a signalized intersection (commonly termed "pre-signals") has been touted as a possible solution to reduce motorist confusion and risky behavior at the crossing.

Users of this Manual may be familiar with commonly used terminology dealing with highway and railroad signaling issues, such as those used in Chapter 8 of the MUTCD (*3*), and provided here:

- **Clear Storage Distance** – the distance available for vehicle storage measured between 1.8 m (6 ft) from the rail nearest the intersection to the intersection stop line or the normal stopping point on the highway. At skewed highway-rail grade crossings and intersections, the 1.8 m (6 ft) distance shall be measured perpendicular to the nearest rail either along the centerline or edgeline of the highway, as appropriate, to obtain the shorter distance. Where exit gates are used, the distance available for vehicle storage is measured from the point where the rear of the vehicle would be clear of the exit gate arm. In cases where the exit gate arm is parallel to the track(s) and is not perpendicular to the highway, the distance is measured either along the centerline or edgeline of the highway, as appropriate, to obtain the shorter distance;
- **Interconnection** – the electrical connection between the railroad active warning system and the highway traffic signal controller assembly for the purpose of preemption;
- **Minimum Track Clearance Distance** – for standard two-quadrant railroad warning devices, the minimum track clearance distance is the length along a highway at one or more railroad tracks, measured either from the highway stop line, warning device, or 3.7 m (12 ft) perpendicular to the track centerline, to 1.8 m (6 ft) beyond the track(s) measured perpendicular to the far rail, along the centerline or edgeline of the highway, as appropriate, to obtain the longer distance. For four-quadrant gate systems, the minimum track clearance distance is the length along a highway at one or more railroad tracks, measured either from the highway stop line or entrance warning device, to the point where the rear of the vehicle would be clear of the exit gate arm. In cases where the exit gate arm is parallel to the track(s) and is not perpendicular to the highway, the distance is measured either along the centerline or edge of the highway, as appropriate, to obtain the longer distance;
- **Minimum Warning Time** – Through Train Movements – the least amount of time active warning devices shall operate prior to the arrival of a train at a highway-rail grade crossing;
- **Preemption** – the transfer of normal operation of highway traffic signals to a special control mode;
- **Pre-signal** – supplemental highway traffic signal faces operated as part of the highway intersection traffic signals, located in a position that controls traffic approaching the highway-rail grade crossing in advance of the intersection;
- **Queue Clearance Time** – the time required for the design vehicle of maximum length stopped just inside the minimum track clearance distance to start up and move through and clear the entire minimum track clearance distance. If pre-signals are present, this time shall be long enough to allow the vehicle to move through the intersection, or to clear the tracks if there is sufficient clear storage distance. If a four-quadrant gate system is present, this time shall be long enough to permit the exit gate arm to lower after the design vehicle is clear of the minimum track clearance distance;

Additional information on the preemption of traffic signals is available in the ITE Recommended Practice (*6*).

This section provides information and AMFs on the safety effect of the following active and passive traffic control devices used at or directly adjacent to railroad-highway grade crossings.

Freeways and expressways are not discussed in this section.

Exhibit 6-5: Resources examined to investigate the safety effect of signals and markings at railroad-highway grade crossings

DOCUMENT	DESCRIPTION	COMMENT
Oh, J., Washington, S.P., and Nam, D., "Accident Prediction Model for Railway-Highway Interfaces", Accident Analysis and Prevention, Vol., 38, 2006, pp. 346-356.	Models were developed to relate crashes at railroad crossings in Korea with the characteristics of the crossings.	Added to synthesis.
(Park, P. Y.-J. and Saccomanno, F.F., "Reducing Treatment Selection Bias for Estimating Treatment Effects Using Propensity Score Method", Journal of Transportation Engineering, Vol. 12 (February 2007), pp. 112-117)	This paper used the propensity score method to reduce treatment selection bias. Using this information AMFs were estimated for different treatments.	Added to synthesis.
(Saccomanno, F.F., Park, P.Y.-I., and Fu, L., "Estimating Countermeasure Effects for Reducing Collisions at Highway-Railway Grade Crossings", Accident Analysis and Prevention, Vol. 39 (2007), pp. 406-416)	This paper used a Bayesian data fusion approach to combine results from previous studies with results from Canadian studies that had examined the safety of railroad grade crossings. Estimates of AMFs were provided for elimination of whistle prohibition and upgrading flashing lights to gates.	Added to synthesis.
(Saccomanno, F.F. and Lai, X., "A Model for Evaluating Countermeasures at Highway-Railway Grade Crossings", Transportation Research Record 1918, pp. 18-25, 2005)	This study used factor analysis along with cluster analysis to divide the sample of crossings into different groups. Negative binomial models were developed for each cluster relating crash frequency with site characteristics.	Added to synthesis.
(Park, Y.-J. and Saccomanno, F.F., "Evaluating Factors Affecting Safety at Highway-Railway Grade Crossings", Transportation Research Record 1918, pp. 1-9, 2005)	This study used the tree-based recursive partitioning method (RPART) to divide the crossings in Canada to 19 classes. Negative binomial regression models were developed relating crash frequency with site characteristics – indicator variables were introduced to represent classes.	Added to synthesis.
(Park, Y.-J. and Saccomanno, F.F., "Collision Frequency Analysis Using Tree-Based Stratification", Transportation Research Record 1908, pp. 121-129, 2005)	Poisson regression models were estimated to relate crashes at crossings with site characteristics. The sample of intersections were classified based on a method called tree-based recursive partitioning method (RPART)	Added to synthesis.
(*13*) (Hauer, E., "Cause and Effect in Observational Cross-Section Studies on Road Safety." (2005))	Study discussing strengths and weaknesses of cross-section safety studies	Added to synthesis for discussion on applicability of railroad-highway grade crossing accident prediction models.
(*14*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	Handbook summarizing the effects of various road safety measures and treatments using a meta-analytical approach.	Added to synthesis. t and s values calculated using available information.
(*7*) (Lerner, N. D., Llaneras, R. E., McGee, H. W., and Stephens, D. E., "NCHRP Report 470: Traffic Control Devices for Passive Railroad-Highway Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (2002))	Includes a detailed critical review of research on the effect of traffic control devices at rail-highway grade crossings; Also evaluated traffic control devices.	Reference suggested by NCHRP 17-18(4). Added to synthesis. Only anecdotal evidence.

DOCUMENT	DESCRIPTION	COMMENT
(*5*) (Korve, H. W., Ogden, B. D., Siques, J. T., Mansel, D. M., Richards, H. A., Gilbert, S., Boni, E., Butchko, M., Stutts, J. C., and Hughes, R. G., "TCRP Report 69: Light Rail Service: Pedestrian and Vehicular Safety." Washington, D.C., Transportation Research Board, National Research Council, (2001))	Presents "before and after" evaluation of the safety effect of pre-signals at highway-rail grade crossings using motorist behavior, not accidents.	Added to synthesis. Only anecdotal evidence.
(Wooldridge, M. D., Fambro, D. B., Brewer, M. A., Engelbrecht, R. J., Harry, S. R., and Cho, H., "Design Guidelines for At-Grade Intersections Near Highway-Railroad Grade Crossings." FHWA/TX-01/1845-3, Austin, Texas Department of Transportation, (2000))	Report provides guidelines for the design of intersections located close to highway-railroad crossings.	Not added to synthesis. No information found on safety impacts—reference only deals with traffic operations (i.e., interconnection, pre-emption) without relating the various recommendations to the safety effects.
(*9*) (Korve, H. W., "NCHRP Synthesis of Highway Practice Report 271: Traffic Signal Operations Near Highway-Rail Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (1999))	Report presents an overview of current practices regarding the operation of traffic signals at intersections located close to highway-rail grade crossings.	Added to synthesis. Only anecdotal evidence of safety improvements found.
(Fambro, D. B., Noyce, D. A., Frieslaar, A. H., and Copeland, L. D., "Enhanced Traffic Control Devices and Railroad Operations for Highway-Railroad Grade Crossings: Third-Year Activities." FHWA/TX-98/1469-3, Austin, Texas Department of Transportation, (1997))	Research evaluated the effectiveness of a vehicle-activated strobe light and supplemental sign enhancements at passive railroad crossings using a before and after study which investigated changes in speed at the crossings, a driver survey and a driver observation study.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Applied Management & Planning Group, "Evaluation of Pedestrian Swing Gates at the Imperial Highway Station." Los Angeles, Calif., Los Angeles County Metropolitan Transportation Authority, (1995))	Before and after evaluation of pedestrian traffic control at light rail station, used frequency of dangerous pedestrian maneuvers as MOE.	Reference suggested by NCHRP 17-18(4). Not added to synthesis. More relevant to Section on Pedestrians and Bicyclists at Railroad-Highway Grade Crossings (Future Edition).
(*11*) (Richards, S. H., Heathington, K. W., and Fambro, D. B., "Evaluation of Constant Warning Times Using Train Predictors at a Grade Crossing with Flashing Light Signals." Transportation Research Record 1254, Washington, D.C., Transportation Research Board, National Research Council, (1990) pp. 60-71.)	Researchers evaluated the effects of train predictors and constant warning time (CWT) on crossing safety and driver response measures (including risky behavior) at a grade crossing with flashing light signals.	Added to synthesis. Only anecdotal evidence and improvements terms of driver behavior found.
(*12*) (Heathington, K. W., Fambro, D. B., and Richards, S. H., "Field Evaluation of a Four-Quadrant System for Use at Railroad-Highway Grade Crossings." Transportation Research Record 1244, Washington, D.C., Transportation Research Board, National Research Council, (1989) pp. 39-51.)	Research examined the safety effectiveness of four-quadrant gates through before and after study of driver behavior.	Reference suggested by NCHRP 17-18(4). Added to synthesis. Only anecdotal and improvements in terms of driver behavior found.
(*15*) (Fambro, D. B., Heathington, K. W., and Richards, S. H., "Evaluation of Two Active Traffic Control Devices for Use at Railroad-Highway Grade Crossings." Transportation Research Record 1244, Washington, D.C., Transportation Research	Study evaluated investigated the effectiveness of two traffic control devices in changing driver behavior using a before-after study approach. The two devices evaluated for potential safety benefits were four-quadrant flashing light signals with overhead	Added to synthesis. Only anecdotal and improvements in terms of driver behavior found.

DOCUMENT	DESCRIPTION	COMMENT
Board, National Research Council, (1989) pp. 52-62.)	strobes and standard highway traffic signals (pre-signals).	
(Bowman, B. L., "The Effectiveness of Railroad Constant Warning Time Systems." Transportation Research Record 1114, Washington, D.C., Transportation Research Board, National Research Council, (1987) pp. 111-122.)	Study of the effectiveness of railroad constant warning time (CWT) systems in reducing motorist violations and vehicle-train accidents using 5 years of crash data.	Not added to synthesis. Only anecdotal evidence and discussion of CWT provided.
(*16*) (Hauer, E. and Persaud, B. N., "How to Estimate the Safety of Rail-Highway Grade Crossings and the Safety Effects of Warning Devices." Transportation Research Record 1114, Washington, D.C., Transportation Research Board, National Research Council, (1987) pp. 131-140.)	Study compared results from previous cross-section and before-after studies that investigated the safety effect of various warning devices at railroad-highway grade crossings.	Some qualitative notes added to synthesis. Results from this particular study already incorporated as part of meta-analysis by Elvik and Vaa (2004).
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))	The handbook provides general information on highway-rail grade crossings including overview of various traffic control devices.	Not added to synthesis. Nothing found on safety except for accident prediction models but use of those models to develop t values not valid.

Based on a critical review of the references identified in Exhibit 6-5, it appears that the many of the studies done to date are based on the use of anecdotal or qualitative evidence of improvements to safety at both active and passive railroad-highway grade crossings. As a result of the inherent difficulty in finding sufficient crash data for railroad-highway grade crossings as described in Section 6.1.2, most studies are focused on the modifications to driver behavior at railroad-highway grade crossings and have concluded that some treatments such as pre-signals and four-quadrant gates are promising in terms of reducing or even eliminating violations and risky driver behavior. Apart from results from Hauer and Persaud (*16*) and Elvik and Vaa (*14*) and more recently by Dr. Saccomanno and his colleagues in Canada (*50*, *51*, *52*, *53*, *54*), none of the other studies reviewed were able to make conclusions based on accident reductions.

As reported by Tustin et al., there are a wide variety of accident prediction models currently in use throughout the U.S. to forecast the number of railroad-highway grade crossing accidents (*1*). These models vary in complexity but all use some combination of input parameters such as the number of tracks, highway traffic approach speeds, train speeds, number of mainline tracks, number of trains, and numerous other factors. These accident prediction models are essentially regression models based on cross-section data and based on findings from research by Hauer and Persaud (*16*).

It appears that the indices of effectiveness derived using such models may be unreliable since the models do not account for policies usually in place when agencies decide on using one type of traffic control device versus another, and other confounding factors that may influence the results of such an analysis. For example, Hauer and Persaud point out that costlier protection devices at railroad-highway grade crossings tend to be used at sites with higher demands on crossing users (such as poor sight distances, downgrades, higher approach speeds, proximity to schools, etc.) and perhaps have a history of accident occurrence (*16*). With such practices in place, it may be unrealistic or unreasonable to calculate indices of effectiveness by taking the ratio of accidents for a crossing with one type of traffic control device over the accidents for a similar crossing with another type of traffic control device. In a more recent study, Hauer stated that, with respect to the treatments at railroad-highway grade crossings, there is "the omnipresent suspicion that entities have trait A but not B for good reason and that these reasons are not fully known and difficult to account for in a regression model" (*13*).

Saccomanno et al., (2007) also acknowledge the limitations of using regression models to determine the effectiveness of engineering treatments, including "variable colinearity, misspecification of inputs, failure to consider higher-order interaction terms, treatment selection bias, and regression-to-the-mean" (*51*). To address some of these limitations, Park and Saccomanno (*54*) use tree-based recursive partitioning method (RPART) to stratify the crossings into meaningful and homogenous classes. Separate regression models were developed for each homogenous class. Park and Saccomanno (*50*) argue that this approach does a better job of separating the effect of countermeasures from other factors such as roadway class and site characteristics, compared to traditional cross-sectional regression models. Following a similar theme, Saccamanno and Lai (*52*) first used factor and cluster analysis and then estimated regression models for each cluster. Park and Saccomanno (*50*) used propensity score method to reduce treatment selection bias in trying to estimate the safety effectiveness of selected treatments at railroad crossings.

Due to the limitations of cross sectional models, Hauer and Persaud (1987) argue that before-after studies are a reasonable approach to estimate the safety effectiveness of countermeasures since there are methods to "cleanse before-and-after comparisons of bias-by-selection" (*16*). However, crashes are relatively rare at railroad crossings and hence, any treatment that is evaluated needs to be implemented at a large number of locations in order to obtain statistically reliable results of its effectiveness. It is also important to note that the indices of effectiveness that are derived from before-after studies represent the average safety effect of the sites examined and as such, the applicability of these values depends on the specific mix of crossing characteristics of the entities being "treated" and studied. The index of effectiveness derived from a before-after study may not apply to some specific cases where the characteristics of a particular crossing are vastly different from those examined in the before-after study.

Treatment: Upgrade crossings with signs to flashing lights and sound signals

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Elvik and Vaa analyzed a number of research studies that examined the safety effect of upgrading the traffic control at crossings from signs to flashing lights and sound signals, and reported that this treatment significantly reduced total grade crossing accidents (p. 579) (*14*). The traffic volumes and environment were not provided in the report. The results from the meta-analysis are summarized in Exhibit 6-6. This study was considered to be of medium-high quality and the standard error value is based on the 95% confidence interval provided by Elvik and Vaa, and a method correction factor of 1.8 was applied to account for the study quality.

Park and Saccomanno (*54*) used RPART to classify the locations into 4 classes and developed poisson regression models to relate crash frequency with site characteristics. Models were developed for each class separately. In addition, one model was developed for all classes combined with indicator variables to represent each class. The relationship between exposure and crashes was assumed to be linear in this model. The type of warning device (flashing lights, gates, or signs) was one of the independent variables in the model. Using the coefficients of these independent variables, AMFs were derived and are shown in Exhibit 6-6. An MCF of 2.0 was applied to the standard errors.

Park and Saccomanno (*53*) also used RPART to classify locations. However, in this study, a larger set of independent variables were used including type of warning device. The RPART procedure produced 19 classes and they were represented as indicator variables in a negative binomial regression model – the indicator variables for six of these classes were statistically significant at the 0.05 significance level. The AMF for upgrading signs to flashing lights on arterial/collector or local roads was estimated to be 0.253. On the other hand, the AMF for upgrading signs to flashing lights on 'other' roads was estimated to be much higher (0.722). Standard errors were not provided for these AMFs.

Saccamanno and Lai (*52*) first used factor and cluster analysis and then estimated regression models for each cluster. The models revealed a 58% reduction in crashes when signs were upgraded to flashing lights (i.e., AMF of 0.42). Standard errors were not provided for these AMFs.

Park and Saccomanno (*50*) used propensity score method to reduce treatment selection bias in trying to estimate the safety effectiveness of selected treatments at railroad crossings. They compared these results with those obtained through a before-after EB method. The propensity score method revealed a 31.7% reduction in crashes when signs were upgraded to flashing lights (i.e., AMF of 0.683). The before-after EB method revealed a reduction of 69.1% reduction (i.e., AMF of 0.309). Standard errors were provided for either of these AMFs.

The results from Elvik and Vaa (*14*) were recommended for the HSM. The meta-analysis results were considered more defensible compared to the cross-sectional models that were developed in several of the studies co-authored by Saccomanno. The EB before-after results from Park and Saccomanno (*50*) could not be used because standard errors were not provided.

Exhibit 6-6: Safety effectiveness of flashing lights and sound signals at railroad-highway grade crossings with only signs

Author, date	**Treatment/ Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa, 2004	Upgrading signs to flashing lights and sound signals.	Not specified.	Not specified.	All grade crossing accidents, severity not specified.	0.50	0.045
(*54*) Park and Saccomman no (2005)	Upgrade signs to flashing lights		Arterial or collector	All grade crossing accidents	0.216	0.053
	Upgrade signs to flashing lights		Local or other roads with multiple tracks	All grade crossing accidents	0.312	0.138
	Upgrade signs to flashing lights		Local roads with single track	All grade crossing accidents	0.212	0.043
	Upgrade signs to flashing lights		Other road types with single track	All grade crossing accidents	0.260	0.230
	Upgrade signs to flashing lights		All	All grade crossing accidents	0.226	0.033

Treatment: Install gates at crossings where previously there were only signs

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Elvik and Vaa examined the safety effect of gates at railroad-highway grade crossings that previously had only signs as traffic control devices.(*14*) The authors conducted a meta-analysis of a number of studies and reported a significant reduction in grade crossing accidents following the implementation of the treatment. The environment and traffic volumes were not provided. The safety effects are summarized in Exhibit 6-7. This study was considered to be of medium-high quality and the standard error value is based on the 95% confidence interval provided by Elvik and Vaa, and a method correction factor of 1.8 was applied to account for the study quality.

Exhibit 6-7 also shows the AMFs that were developed from the poisson regression models estimated by Park and Saccomanno (*54*) (MCF of 2.0 was applied to the standard errors from this study). Saccomanno and Lai (*52*) found a 63% reduction in crashes when gates were introduced at locations with signs; as mentioned earlier, this study used factor and cluster analysis along with negative binomial regression (standard errors were not available in the paper). When propensity scores were used, Park and Saccomanno (*50*) reported a 47.6% reduction in crashes when gates were introduced; the same study also reported 84.6% reduction in crashes when a before-after EB method was utilized (standard errors were not provided in both cases).

The results from Elvik and Vaa (*14*) were recommended for the HSM. The meta-analysis results were considered more defensible compared to the cross-sectional models that were developed in several of the studies co-authored by Dr. Saccomanno. The EB before-after results from Park and Saccomanno (*50*) could not be used because standard errors were not provided.

Exhibit 6-7: Safety effectiveness of gates at railroad-highway grade crossings with only signs previously

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing gates at crossings with signs.	Not specified.	Not specified.	All grade crossing accidents, severity not specified.	0.33	0.09
(*54*) Park and Saccomanno (2005)	Installing gates at crossings with signs.		Arterial or collector	All grade crossing accidents	0.064	0.018
	Installing gates at crossings with signs.		Local or other roads with multiple tracks	All grade crossing accidents	0.132	0.050
	Installing gates at crossings with signs.		Local roads with single track	All grade crossing accidents	0.091	0.033
	Installing gates at crossings with signs.		Other road types with single track	All grade crossing accidents	0.340	0.536

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
	Installing gates at crossings with signs.		All	All grade crossing accidents	0.066	0.013

Treatment: Install gates at crossings where previously there were only flashing lights and sound signals

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Using a meta-analysis of several studies, Elvik and Vaa investigated the safety effect of installing gates at railroad-highway grade crossings that previously had only flashing lights and sound signals as traffic control devices.(*14*) The traffic volumes and environment were not provided in the report. The results from the meta-analysis are summarized in Exhibit 6-8. This study was considered to be of medium-high quality and the standard error value is based on the 95% confidence interval provided by Elvik and Vaa, and a method correction factor of 1.8 was applied to account for the study quality. The AMFs from Elvik and Vaa were recommended for inclusion in the HSM.

Saccomanno and Lai (2005) reported a 13% reduction in crashes when gates were introduced at crossings that originally had flashing lights; this study used negative binomial regression along with cluster analysis (standard errors were not provided). When the propensity score method was used, Park and Saccomanno (2007) found a 24.4% reduction in crashes; when a before-after EB method was used, the reduction was 71.3% (standard errors were not reported).

Saccomanno et al. (2007) used Bayesian data fusion approach to combine results from three previous studies conducted by Saccomanno and his colleagues in Canada with other previous studies conducted mainly using data from the United States. As an example, AMFs were derived for upgrading flashing lights to gates for a specific type of road: local roads, single track, track angle of 70 degrees, AADT of 15,000, 12 daily trains, posted speed limit of 50 km/h, and maximum train speed of 10 mph. The results were a bit different depending on whether the posterior distribution was normal or beta. The AMF was 0.669 with a normal distribution and 0.618 with a posterior distribution. Since these results are applicable to very specific conditions, they are not included in Exhibit 6-8.

Exhibit 6-8: Safety effectiveness of gates at railroad-highway grade crossings with only flashing lights and sounds signals

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Installing gates at crossings with flashing lights and sound signals.	Not specified.	Not specified.	All grade crossing accidents, severity not specified.	0.55	0.09

Discussion: Impact of STOP and Yield signs at passive railroad-highway grade crossings

Lerner et al. discussed the use of STOP and Yield signs at passive railroad-highway grade crossings and concluded that despite the selective practice of using STOP signs at some grade crossings for many years and despite several field studies, "the effectiveness of STOP signs for general use appears unresolved and controversial" (*7*). In terms of Yield signs, the researchers found that there seems to be growing support for the use of these types of treatments at passive railroad-highway grade crossings, particularly since drivers are supposed to yield the right-of-way to oncoming trains. No evidence was presented to support this treatment in terms of either positive changes in driver behavior or crash reductions.

Discussion: Impact of pre-signals on driver behavior

Korve et al. stated that pre-signals have already been recommended by the U.S. DOT's Technical Working Group (TWG) in certain locations; specifically, at highway-rail grade crossings where the clear storage distance cannot accommodate the design vehicle, typically a large truck (*9*). Pre-signals control traffic entering the highway-rail grade crossing, thereby circumventing potential vehicle-train conflicts so long as there is compliance with the pre-signals. According to the research reviewed, most agencies view traffic pre-signals as providing relatively consistent service with few malfunctions; motorists tend to understand and obey them more readily than flashing light signals, especially if traffic signals are enforced by the local police authority.

This treatment appears to be particularly effective in reducing risky driver behavior in the vicinity of railroad-highway grade crossings. For instance, Fambro et al. investigated the safety effectiveness of pre-signals using a before-after study of driver behavior and found that the treatment reduced the number of crossings per signal activation and the risky behavior per train arrival from 3.35 to 0.73 and from 0.13 to 0.05 respectively (*15*). Risky behavior was defined by Fambro et al. to be the number of vehicles crossing while the flashing light signals are activated and within 10 seconds of the train's arrival. In terms of other driver response measures, the highway traffic signal did not significantly change the approach speed profile, the perception-brake reaction time, or the maximum deceleration level. There were also no apparent negative effects such as accidents, confusion, diversions, or unnecessary delay attributed to the treatment (*15*). Based on these findings, the researchers concluded that the highway traffic signal proved to be feasible and effective as a grade crossing traffic control device that outperforms standard flashing light signals on key safety and driver response measures (*15*).

This finding appears to be substantiated with the results from a similar research study by Korve et al. As part of the research effort to improve the safety of light rail transit (LRT) in semi-exclusive rights-of-way, Korve et al. conducted a before-after study of motorist driving behavior to investigate the effectiveness of pre-signal treatments at railroad-highway grade crossings for LRT. Two urban sites were examined and the researchers found that the use of pre-signals reduced the number of motorists in the clear storage distance at one site by 93% on average and 80% on average at the second site (*5*). The authors also found that pre-signals reduced the number of vehicles in the minimum track clearance distance but the results were not statistically significant. On average, the treatment also reduced right turns on red (when prohibited) by 82% (*5*). By conducting a cross-sectional analysis, Korve et al. also concluded that the use of the Keep Clear Zone striping reduced the number of vehicles that stopped in the clear storage distance or in the minimum track clearance distance by 93% (*5*). From the information provided in the reference, it is unclear if this cross-sectional comparison is appropriate given that the traffic volume at the site with the Keep Clear Zone striping had about half the vehicular traffic volume (10,000 ADT) of the site without (20,000 ADT), with both experiencing train volumes in excess of 40 trains per day.

Discussion: Impact of constant warning time devices on driver behavior

Richards et al. investigated the effectiveness of train predictors to provide constant warning times at a single track railroad-highway grade crossing and found that this particular treatment significantly reduced the frequency of incidences of risky driver behavior (*11*). Risky driver behavior was defined in terms of the number of vehicles crossing the tracks between activation of the warning device and the train's arrival at the crossing. Based on a comparison of the frequencies of vehicle crossings after activation of the warning devices, Richards et al. found that the treatment "significantly reduced" the average number of vehicles crossing per train arrival from 10.86 to 3.35 (*11*). Although this measure of effectiveness is dependent on the traffic and train volumes at the crossing, Richards et al. concluded that the installation of train predictors (and the resulting constant warning times) led to fewer excessively long warning times at crossings. This in turn reduces incidences of risky driver behavior, improving the overall safety and enhanced driver respect for flashing light signals (*11*). The researchers also reported that approach speeds of vehicles, driver reaction times and deceleration behavior (braking) were not adversely affected (*11*).

Discussion: Impact of four-quadrant gates on violations

Heathington et al. investigated the effectiveness of a four-quadrant gate system using a before-after study approach (*12*). Heathington et al. found that the treatment did not result in any changes to driver behavior, particularly when examined from the perspective of vehicle speeds approaching the railroad-highway grade crossing, perception-brake reaction times, and deceleration levels (*12*). However, the treatment resulted in the complete elimination of vehicles driving around gates and reduced the average number of vehicles crossing while the gate arms were being lowered from 4.01 to 1.13 for vehicles crossing per train arrival, or 96.8 to 54.7% of trains (*12*). With the implementation of the treatment, no vehicles crossed within 20 seconds of the train's arrival at the crossing, suggesting that the treatment was effective in "eliminating risky and illegal behavior[1]" (*12*).

Discussion: Impact of four-quadrant flashing light signals on driver behavior

Fambro et al. investigated the safety effectiveness of four quadrant flashing light signals with overhead strobes using driver performance measures such as vehicle approach speeds, perception-brake reaction times, and violation and vehicle crossing rates (*15*). The authors found that four-quadrant flashing light signals with strobes "did not significantly affect violations, clearance times, approach speed profiles, maximum deceleration levels or perception-brake reaction times" (*15*). There were also no accidents, confusion, or motorist diversions with the implementation of the treatment. The researchers concluded that four-quadrant flashing light signals with strobes offered no apparent driver response or safety advantages over standard two-quadrant flashing signals (*15*).

[1] Heathington et al. defined four categories of driver behavior as they relate to the clearance time. The clearance time is the difference in time between the last vehicle to cross and the train's arrival at the crossing. The four categories are: Risky – less than 10 seconds; Aggressive – from 10 to 20 seconds; Normal – from 20 to 30 seconds; Cautious – greater than 30 seconds (*12*).

6.1.3. Pedestrians and Bicyclist Safety at Railroad-Highway Grade Crossings [Future Edition]

Rail agencies and others are concerned with the large volumes of trespassers into areas designated to train movements. The safety effectiveness of some measures to control expected and undesirable movements may be discussed in this section in future editions of the HSM. Treatments may include: pedestrian traffic control, signage, pedestrian and cyclist gates, crossings and sidewalk designs, accessibility, and grade separated facilities. Potential resources are listed in Exhibit 6-9.

Exhibit 6-9: Potential resources on the pedestrian and bicyclist safety considerations at railroad-highway grade crossings

DOCUMENT
(Korve, H. W., Ogden, B. D., Siques, J. T., Mansel, D. M., Richards, H. A., Gilbert, S., Boni, E., Butchko, M., Stutts, J. C., and Hughes, R. G., "TCRP Report 69: Light Rail Service: Pedestrian and Vehicular Safety." Washington, D.C., Transportation Research Board, National Research Council, (2001))
(Applied Management & Planning Group, "Evaluation of Pedestrian Swing Gates at the Imperial Highway Station." Los Angeles, Calif., Los Angeles County Metropolitan Transportation Authority, (1995))
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))
(Staplin, L., Lococo, K., Byington, S., and Harkey, D., "Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians." FHWA-RD-01-051, Washington, D.C., Federal Highway Administration, (2001))
(Farran, J. I., Korve, H. W., Levinson, H. S., and Mansel, D., "The Light Rail Transit Safety Experience." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 97-103.)

6.1.4. Safety Effects of Other Railroad-Highway Grade Crossing Elements

This section of the HSM provides information on the safety effects of the various secondary design and operational elements of railroad-highway grade crossings. The following section discusses the safety impact of artificial illumination at railroad-highway grade crossings. Sections dealing with the use of different grade crossing materials, as well as the safety issues related to the presence of hazardous materials vehicles, trucks, school buses and other transit vehicles in the vicinity of grade crossings may be included in future editions of the HSM.

6.1.4.1. Illumination

Artificial illumination is occasionally provided at railroad highway grade crossings. This section presents evidence regarding the safety effect of illumination of railroad-highway grade crossings. This refers to the introduction of artificial lighting of railroad-highway grade crossings that did not have it.

Future editions of the HSM may include discussions of "tall flexible posts" and "traffic dots" at railroad (LRT) crossings.

Exhibit 6-10: Resources examined to investigate the safety effect of illumination at railroad-highway grade crossings

DOCUMENT	DESCRIPTION	COMMENT
(Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Collisions Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Several strategies aimed at reducing crashs involving older drivers.	No AMFs. Not added to synthesis.
(Wooldridge, M. D., Fambro, D. B., Brewer, M. A., Engelbrecht, R. J., Harry, S. R., and Cho, H., "Design Guidelines for At-Grade Intersections Near Highway-Railroad Grade Crossings." FHWA/TX-01/1845-3, Austin, Texas Department of Transportation, (2000))	Research performed in cooperation with the Texas DOT with respect to the deign guidelines of at-grade intersections near highway-railroad crossings.	No AMFs. Not added to synthesis.
(*17*) (Elvik, R., "Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure." Transportation Research Record 1485, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 112-123.)	A meta-analysis of 37 studies, containing a total of 142 results from 1948 to 1989.	Added to synthesis.
(Mather, R. A., "Seven Years of Illumination at Railway-Highway Crossings." Transportation Research Record 1316, Washington, D.C., Transportation Research Board, National Research Council, (1991) pp. 54-57.)	The results of 34 crossings that were installed during the first 7 years of illumination in Oregon.	Too few details to be included in meta-analysis.
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))	Handbook providing information on railroad-highway crossings, including characteristics of the crossing environment and users with physical and operational characteristics.	No AMFs. Not added to synthesis.

One before and after study (Mather ,1991) was found that evaluates safety effects of illumination of railroad-highway grade crossings, using 34 railroad-highway grade crossings in the state of Oregon (*18*). According to this study, the number of accidents in darkness was reduced from 18 before 1985 (length of period not stated) to 3 in the years 1985 to 1989, when the illumination program was conducted. Mather states that, “Because the sample is small, it is statistically invalid to draw many definite conclusions.” (p. 56) (*18*).

Evidence regarding the effect of intersection illumination is taken from a meta-analysis of 37 evaluation studies containing 142 estimates of effect (*17*). This analysis has subsequently been updated by the addition of new studies, increasing the number of studies to 40 and the number of estimates of effect to 152.

Results of studies that deal specifically with illumination in intersections have been selected. There are 32 estimates of effect that refer to intersections. State-of-the-art techniques of meta-analysis have been applied to synthesize these estimates of effect.

Studies have been classified in three groups according to study quality. Studies rated as high quality include studies using both an internal and external comparison group (the distinction between external and internal comparison is explained below) and matched case-control studies. Studies rated as medium quality include studies that provide data on traffic volume in addition to accident data, and studies using an external comparison group only. Studies rated as low quality include studies that use only an internal comparison group and simple (as opposed to matched) case-control studies. Most studies, representing 74% of the estimates of effect, have been rated as low quality. Standards errors have been adjusted by a factor of 1.2 in high quality studies (all study designs), 2 in medium quality before-after studies, and 3 in low quality before-after studies. In case-control or cross-section studies, standard errors were adjusted by a factor of 3 medium quality studies and a factor of 5 in low quality studies.

Exhibit 6-11 shows summary estimates of the effects of lighting on accidents. Uncertainty in summary estimates of effect is stated as adjusted standard error. All estimates of effect refer to accidents in darkness only. Two sets of summary estimates of effect are presented. The first set is based on conventional meta-analysis. The second set has been generated from coefficients estimated in meta-regression analysis. In theory, the meta-regression estimates are superior to the conventional summary estimates, since meta-regression controls for more confounding factors or imbalance in the distribution of estimates across moderator variables (a moderator variable is any variable that influences the size of the effect of a measure on accidents).

Exhibit 6-11: Summary estimates of the effects on accidents of public lighting in intersections

Accident type	**Accident severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Summary estimates based on conventional meta-analysis			
Intersection accidents	*Fatal accidents*	*No study*	*No study*
	Injury accidents (16)	*0.624*	*0.126*
	PDO-accidents (5)	*0.688*	*0.361*
Summary estimates based on meta-regression analysis			
Intersection accidents	Fatal accidents	0.228	0.282
	Injury accidents	0.504	0.205
	PDO-accidents	0.515	0.214

Only estimates that specify accident severity have been used. Estimates referring to “all” accidents, which is usually a mixture of injury accidents and property-damage-only accidents have been discarded. The number of estimates underlying each summary estimate is stated in parentheses.

No study estimating the effect of intersection illumination on fatal accidents has been found. Both injury accidents and property damage only accidents appear to be reduced. It is unclear why the effect attributed to illumination is larger according to the meta-regression analysis than it is for the conventional meta-analysis.

It is fairly common in road safety evaluation research to find that more well-controlled studies attribute a smaller effect to the measure evaluated than less well-controlled studies. In this case, the meta-regression approach must be considered as a more well-controlled approach to meta-analysis than the conventional approach. Unexpectedly, the effects attributed to road lighting are larger in the meta-regression approach than in the conventional approach.

6.1.4.2. Closely Spaced Intersections or Access Points [Future Edition]

The proximity of a railroad-highway grade crossing to other intersections (or access points) may be related to the safety performance of the crossing. Future editions of the HSM may discuss this relationship in this section. The distance is generally designed to provide sufficient vehicle storage based on the expected queue lengths to prevent spillover of vehicles queuing on the tracks when a train approaches. Potential resources are listed in Exhibit 6-12.

Exhibit 6-12: Potential resources on closely spaced intersections to railroad-highway grade crossings and safety

DOCUMENT
(Institute of Transportation Engineers, "Preemption of Traffic Signals Near Railroad Crossings: Version 11." Washington, D.C., Institute of Transportation Engineers, (2004))
(Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R., "NCHRP Report 500 Volume 12: A Guide for Addressing Collisions at Signalized Intersections." Washington, D.C., Transportation Research Board, National Research Council, (2004))
(Lerner, N. D., Llaneras, R. E., McGee, H. W., and Stephens, D. E., "NCHRP Report 470: Traffic Control Devices for Passive Railroad-Highway Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (2002))

6.1.4.3. Crossing Surface Materials [Future Edition]

In future editions of the HSM, this section may include information on the safety impact of various roadway surface materials at railroad-highway grade crossings. Potential resources are listed in Exhibit 6-13.

Exhibit 6-13: Potential resources on the safety effects of improving the crossing surface of a railroad-highway grade crossing

DOCUMENT
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))
(Lerner, N. D., Llaneras, R. E., McGee, H. W., and Stephens, D. E., "NCHRP Report 470: Traffic Control Devices for Passive Railroad-Highway Grade Crossings." Washington, D.C., Transportation Research Board, National Research Council, (2002))

6.1.4.4. Hazardous Materials and Truck Routes [Future Edition]

Future editions of the HSM may include discussion of the safety impact of routing hazardous materials and trucks on highways with railroad grade crossings. Potential resources are listed in Exhibit 6-14.

Exhibit 6-14: Potential resources on the safety effects of hazardous materials and truck routes at railroad crossings

DOCUMENT
(Bowman, B. L., McCarthy, K. P., and Hughes, G., "The Safety, Economic and Environmental Consequences of Requiring Stops at Railroad-Highway Crossings." Transportation Research Record 1069, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 117-125.)
(Tustin, B. H., Richards, H., McGee, H., and Patterson, R., "Railroad-Highway Grade Crossing Handbook - Second Edition." FHWA TS-86-215, McLean, Va., Federal Highway Administration, (1986))

6.1.4.5. Transit and School Buses [Future Edition]

Future editions of the HSM may provide discussion in this section of the safety impact of passenger and school buses at railroad-highway grade crossings, and the effects of such vehicles stopping at all crossings. Potential resources are listed in Exhibit 6-15.

Exhibit 6-15: Potential resources on the safety effects of passenger and school buses at railroad crossings

DOCUMENT
(Bowman, B. L., McCarthy, K. P., and Hughes, G., "The Safety, Economic and Environmental Consequences of Requiring Stops at Railroad-Highway Crossings." Transportation Research Record 1069, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 117-125.)

6.2. Work Zones

Work zones may present major disruptions in driving speed, driving characterisitcs and driver expectancy and it is generally accepted that there may be an increase in the number of accidents while a work zone is in place. Accidents in work zones can cause major delays and congestion, paralyzing peak hour traffic.

Rigorous work zone studies are difficult to conduct due to the great variations in work zone design and circumstances. In additon to the usual issues of ADT, type of traffic, weather, illumination, posted speed limit, accident reporting levels, etc., work zone studies must contend with a possible drop in volumes, especially in urban areas, as well as a great variation in the work zone characteristics.

Important work zone issues include:

- How can safety be addressed while keeping traffic moving through a work zone?
- What is the safety effect of closing as many lanes as possible so that the work can be completed quickly? Is it better from a safety perspective to proceed more slowly and to allow traffic to use as many lanes as possible?
- Do work crew protection devices and procedures affect the safety of the traveling public?
- Are work zone strategies that include, for example, technological improvements that can shorten work zone duration or a bonus/penalty for early/late completion of the project, justified by safety improvements?
- What is the safety effect of detours, especially through urban areas with residential traffic and pedestrians?

There are few reliable AMFs found in available literature addressing treatments used in work zones. Many studies compare the accident experience “before” and “during” the work zone. Since the presence of a work zone of any type is not a safety treatment, the use of AMFs that compare a road segment with and without a work zone differs from the use of AMFs elsewhere in the HSM. Where specific treatments are investigated, the duration of the work zone may be too short to record enough accidents to analyze. In addition, small samples, the problem of matching “before” data to the work zone’s length, duration and time of year, and the problem of comparing work zones with differing characteristics mean that some of the information on the safety effects of work zone design and treatments remain tentative. A recently completed NCHRP study entitled “Traffic Safety Evaluation of Nighttime and Daytime Work Zones” provides useful insight into the safety of conducting work with and without lane closures during day and night.

FHWA's "Work Zone Operations Best Practices Guidebook" (*19*) is a valuable resource, along with the FHWA Work Zone website (http://ops.fhwa.dot.gov/wz/index.asp), and the National Work Zone Safety Information Clearinghouse (http://wzsafety.tamu.edu/).

6.2.1. Safety Effects of Work Zone Design Elements

Many traffic, road, and work type characteristics are the basis for selecting design elements of work zones. Work zone design elements include duration, length, and time of day; lane closure design; lane closure merge design; centerline treatments; and other design elements. The safety effect of these elements is discussed in the following sections.

6.2.1.1. Duration, Length, and Time of Day

This section comprises elements of a work zone such as duration (number of days), length (in kilometers or miles) and time of the day (day or night) when the work is taking place. The aspect of driver familiarity or lack of, with the work zone is brought in the context of these elements and the overall safety performance.

The questions of whether accidents are more likely to occur during the early period of construction work compared with the later periods of construction work and whether nighttime work zones offer advantages daytime work zones are discussed.

At present, there is a lack of safety information about the following elements:

- Many short versus one longer work zone;
- Whether it is worthwhile to offer a bonus/penalty for early/late completion of the project;
- Whether it is worthwhile to concentrate on developing technological improvements that can shorten work zone duration;

Many agencies have started conducting work at night to reduce traffic disruption and delay to the driving public. Possible challenges with nighttime work zones include the changeover period each morning and evening, a longer overall work zone presence, shift work problems leading to accidents among construction workers, and noise and light problems in residential areas. Recent work has indicated that nighttime work does produce "negative impacts on the workers' sleep patterns, body rhythms, and social and family lives" (*56*).

There is a need to quantify the safety impact of the duration, construction stage, length, and time of day of work zones on rural and urban roads of all types and for all accident types and severities.

Exhibit 6-16: Resources examined to investigate the safety effect of the duration, construction stage, length, and time of day of work zones

DOCUMENT	DESCRIPTION	COMMENT
(Ullman, G.L., Finley, M.D., Bryden, J.E., Srinivasan, R., and Council, F.M., "Traffic Safety Evaluation of Nighttime and Daytime Work Zones", Draft Final Report on NCHRP Project 17-30, Submitted May 2008)	A detailed study of the safety aspects of daytime and nighttime work zones using data from 5 States. Empirical Bayes methods were used to assess the impacts of conducting work at day and night with and without lane closures.	Added to synthesis. AMFs with standard errors are provided in an exhibit.
(Li, Y., and Bai, Y., "Comparison of Characteristics between Fatal and Injury Accidents in the Highway Construction Zones", Safety Science, Vol. 46 (2008), pp. 646-660.)	This study compared the characteristics of fatal and injury crashes that occurred in Kansas work zones from 1992 to 2004.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
Arditi, D., Lee, D.-E., and Polat, G., "Fatal Accidents in Nighttime versus Daytime Highway Construction Work Zones", Journal of Safety Research, Vol. 38 (2007), pp. 399-405.	This study used FARS data to compare fatal accidents that occurred in nighttime and daytime work zones in Illinois from 1996 to 2001.	Added to synthesis
(*14*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	Limited qualitative information. Added to synthesis.
Holguin-Veras, J., Ozbay, K., Baker, R., Sackey, D., Medina, A., and Hussain, S., "Toward a Comprehensive Policy of Nighttime Construction Work", Transportation Research Record 1861, 2003, pp. 117-124.	This study tried to produce a policy for nighttime construction work by considering the travel time savings, impact of workers' human factors, and impact of pay differentials.	Added to synthesis
(*20*) (Khattak, A. J., Khattak, A. J., and Council, F. M., "Effects of Work Zone Presence on Injury and Non-Injury Crashes." Accident Analysis and Prevention, Vol. 34, No. 1, Oxford, N.Y., Pergamon Press, (2002) pp. 19-29.)	The authors used regression models to investigate the number of expected crashes by work zone duration (number of days) and work zone length.	Suggested by NCHRP 17-18(4). Added to synthesis.
(*21*) (Tarko, A. P. and Venugopal, S., "Safety and Capacity Evaluation of the Indiana Lane Merge System Final Report." FHWA/IN/JTRP-2000/19, West Lafayette, Ind., Purdue University, (2001))	The study evaluated the Indiana Lane Merge System (ILMS) using procedures that combined crash-based and conflict-based crash prediction models to evaluate the safety effects of the ILMS in a real construction zone.	Added to synthesis.
(Pesti, G., Jessen, D. R., Byrd, P. S., and McCoy, P. T., "Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999))	The paper evaluated the operational effects of the Late Merge concept in reducing queues and road rage at work zones. The study used traffic conflicts (forced merges, lane straddles and lane blocking) as a measure of safety effectiveness.	No relevant information for this section. Not added to synthesis.
(Pal, R. and Sinha, K. C., "Analysis of Crash Rates at Interstate Work Zones in Indiana." Transportation Research Record 1529, Washington, D.C., Transportation Research Board, National Research Council, (1996) pp. 43-53.)	The authors used regression models to investigate the number of expected crashes at crossover and partial lane closure sites by work zone duration (number of days).	No relevant results for this section. Not added to synthesis.
(*22*) (Rouphail, N. M., Mousa, R., Said, K., and Jovanis, P. P., "Freeway Construction Zones in Illinois: A Follow-Up Study. Final Report." FHWA/IL/RC-004, Springfield, Illinois Department of Transportation, (1990))	The study evaluated various traffic control measures used in work zones.	Added to synthesis. Provides information on construction stage.
(*23*) (Rouphail, N. M., Yang, Z. S., and Fazio, J., "Comparative Study of Short- and Long-Term Urban Freeway Work Zones." Transportation Research Record 1163, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 4-13.)	Comparative study of crash experience at long-term and short-term freeway work zones.	Suggested by NCHRP 17-18(4). Added to synthesis. Limited information. No AMFs.
(McCoy, P. T. and Peterson, D. J., "Safety Effects of Two-Lane Two-Way Segment Length Through Work	The study's objective was to determine the safety effects of lengthening TLTW segments.	Suggested by NCHRP 17-18(4). Limited

DOCUMENT	DESCRIPTION	COMMENT
Zones on Normally Four-Lane Divided Highways." Transportation Research Record 1163, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 15-21.)	Five speed distribution parameters were used as indicators of traffic safety.	information, now out of date. Not added to synthesis. No AMFs.
(*24*) (Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	The study analyzed accidents that occurred before and during construction in 79 zones in seven states in the 1970s.	Added to synthesis. Limited information. No AMFs.

Several studies have investigated work zone duration, length and time of work, but most of the information available is qualitative and could not be used to establish AMFs. One problem is that work zone length and duration cover a wide range of possibilities. Work zone duration, for example, can range from a few hours to many months. Each study had its own definition of “short” and “long” which sometimes overlap and are not always defined.

The most recent (2002) study available, by Khattak et al., used negative binomial models to investigate the number of expected crashes by work zone duration (number of days) and work zone length (distance) (*20*). The study investigated 36 construction zones at rural and urban locations in California in its sample, which, although small, is larger than the samples used in most previous studies.

For convenience, Khattak et al.’s model is introduced here, and will be referred to in the discussions of work zone duration and length in this section. The explanatory variables in the model were duration of the work zone (days), work zone length (km), ADT, an exposure term intended to capture interactive effects of work zone duration, length and ADT, and a location variable (urban/rural). As the data files used did not contain work zone traffic volumes, Khattak et al. assumed that ADT remained constant. Because ADT volumes are likely to decrease during construction, or to have a different daily distribution, the results are considered to be conservative estimates. There is probably a greater effect of traffic volumes on traffic crashes than the analysis and modeling show. The model is shown in Equation 6-1. Note that the average ADT at the 36 work zones was 101,000 veh/day, but ranged from 4,000 to 237,000 veh/day. The urban location variable and exposure term were not found to be statistically significant (*20*).

Equation 6-1: Model to predict number of expected crashes by work zone duration (number of days) and work zone length (distance) (20)

$$Y = (x_1)^{1.2659} (x_2)^{1.1149} (x_3)^{0.6718} \exp(-0.2257x_4)\exp(-0.5126x_5)\exp(0.1988x_6)\exp(-17.7748)$$

Where

Y is expected number of total crashes in a given duration on work zone segments

x_1 is average ADT of the work zone (veh/day)

x_2 is duration of observation (days)

x_3 is length of the work zones (km)

x_4 is 1 if the work zone is in an urban area, 0 otherwise

x_5 is 1 if injury producing crash, 0 otherwise

x_6 is 1 if crashes recorded during work zones, 0 otherwise

Treatment: Change duration of work zones

Rural two-lane roads; Rural multi-lane highways

No studies found.

Freeways; Expressways

Khattak et al.'s study investigated the safety effects of work zone duration at a mixture of urban and rural freeway sites (*20*). The duration of the work zones observed ranged from 16 days to 714 days. Traffic volumes varied greatly at the sites studied.

Khattak et al.'s model (Equation 6-1) showed that crash frequencies (for all crash types and severities combined, and for injury and non-injury severities separately) increased with increasing work zone duration. As Khattak et al. state, "The estimated parameter for work zone duration is slightly higher than unity, indicating a greater than one-to-one correspondence between crash frequency and duration of observation. According to the model results, a 1% increase in duration of observation will result in a 1.1149% increase in crash frequency" (page 25) (*20*). In other words, if a fictional 7-day work zone experienced 100 crashes (all types, all severities), extending that work zone to 7.5 days (a 7% increase) would result in an 8% increase in crashes (i.e., 7% increase in duration x 1.1149% increase in crashes = 8% more crashes = AMF of 1.08), or 108 crashes (all types, all severities) (Equation 6-2), when all other variables are kept constant. The standard error for this AMF may be calculated from the z-statistic for the model parameter given by Khattak et al.; a method quality descriptor of medium-low was assigned to this study due to the small number of factors that were included in the model. For a 1% increase in duration, the standard error is minimal (i.e., 0.0023). However, as the percent increase in duration becomes larger, so does the standard error, in a non-linear way. Therefore, a fixed standard error cannot be provided for this accident modification function.

Equation 6-2: AMF for percent increase in work zone duration (20)

$$AMF_{all} = 1 + (\text{\% increase in duration} * 1.1149)/100$$

Where:

AMF_{all} is the accident modification factor for all crash types and all severities in the work zone

% increase in duration is the change in duration (# days) of the work zone presence

Khattak et al. conclude that the crash frequency at the work zones on the freeways "increased with higher values of work zone duration" (page 29) and that by "reducing work zone duration, reductions in both injury and non-injury crashes can be achieved" (page 29) (*20*).

Tarko and Venugopal evaluated the Indiana Lane Merge System (ILMS) using procedures that combined crash-based and conflict-based crash prediction models for four-lane divided rural freeways (*21*). Tarko and Venugopal commented, "The duration of work turned out to be a significant factor in all cases. For almost all the cases, the factor was approximately one. This shows that the number of crashes increases almost linearly with the duration" (page 52) (*21*). However, AMFs were not available from this study.

Rouphail et al. compared long- and short-term (intermittent) work zones on urban freeways in a 1988 study (*23*). The 23 "short-term work zones" were intermittent zones where construction took place during six-hour closures. The three "long-term work zones" were longer than four days. All these sites might be considered short-term in other studies. Rouphail et al. were unable to obtain ADT data for the year when the study was conducted, but because all the sites were short-term or relatively short-term, the researchers concluded that motorists were not advised of the work zones and “flow rates should not be expected to vary considerably during construction” (page 5) (*23*).

At the intermittent work zones, Rouphail et al. found that the accident rate was similar to the rate during the before construction period, but at the “long-term” work zones, Rouphail et al. found that accidents increased by 88% compared with the before period and that “rear-end accidents increased significantly” (page 6), but accident severity decreased (*23*). However, AMFs were not available from this study.

Urban and suburban arterials

No studies found.

Treatment: Change work zone length

Rural two-lane roads; Rural multi-lane highways

No studies found.

Freeways; Expressways

Khattak et al.’s study investigated the safety effects of work zone duration at a mixture of urban and rural freeways sites (*20*). The length of the work zones ranged from 0.51 mi (0.83 km) to 12.20 mi (19.53 km). The average length was 4.21 mi (6.73 km). The average ADT at the 36 work zones was 101,000 veh/day, but ranged from 4,000 to 237,000 veh/day.

Khattak et al.’s model (Equation 6-1) showed that crash frequencies increased with increasing work zone length. “According to the model results, a 1% increase in ….segment length will increase crash frequency by 0.6718%” (page 25) (*20*). In other words, if a fictional 5 km work zone experienced 100 crashes (all types, all severities), extending that work zone to 5.25 km (a 5% increase) would result in an 3% increase in crashes (i.e., 5% increase in length x 0.6718% increase in crashes = 3% more crashes = AMF of 1.03), or 103 crashes (all types, all severities) (Equation 6-3), when all other variables are kept constant. The standard error for this AMF may be calculated from the z-statistic for the model parameter given by Khattak et al.; a method quality descriptor of medium-low was assigned to this study due to the small number of factors that were included in the model. For a 1% increase in length, the standard error is minimal (i.e., 0.0013). However, as the percent increase in length becomes larger, so does the standard error, in a non-linear way. Therefore, a fixed standard error cannot be provided for this accident modification function.

Equation 6-3: AMF for % increase in work zone length (km) (20)

$$AMF_{all} = 1 + (\%\text{ increase in length} * 0.6718)/100$$

Where: AMF_{all} is the accident modification factor for all crash types and all severities in the work zone

% increase in length is the change in length (km) of the work zone

Khattak et al. do not appear to draw any further conclusions regarding work zone length.

Tarko and Venugopal’s evaluation of the Indiana Lane Merge System (ILMS) included the length of the work zone as a factor in the model developed (*21*). The authors did not expect the length of the work zone to affect crashes on the approaches to work zones, but found that the length of the work zone “turned out to be statistically very significant for two cases, total rear end crashes and rear end PDO crashes” (page 51) (*21*).

Tarko and Venugopal also comment that "Even more surprising and counter-intuitive was the sign of the length variable…..indicating that shorter work zones had a larger number of merging crashes than longer work zones given that other factors remained the same" (page 51). Tarko and Venugopal suggested that the explanation might be that long (distance) work zones tend to be of greater duration, more intensive traffic management would be in place compared to short work zones and this might make drivers more cautious (page 51) (*21*). No AMFs could be derived from this study.

Urban and suburban arterials

No studies found.

Discussion: Operate work zones in the daytime or nighttime

Rouphail et al. commented that Shepard and Cottrell (1985) "alluded to the potential benefit of night work zone activities but provided no information regarding their accident experience" (*23*) (page 5). Arditi et al. (2007) used data on fatal accidents in construction zones in Illinois from 1996 to 2001 to assess the safety of daytime and nighttime construction zones (*57*). In order to account for exposure, information from Wunderlich and Hardesty (*58*) were used to determine the percentage of work zones where work was done during the day and the percentage of work zones where work was done at night. Arditi et al. concluded that "nighttime construction is about five times more hazardous than daytime construction". However, it is important to note that although Arditi et al. (*57*) tried to account for the number of daytime and nighttime work zones, they did not explicitly account for the fact that more of the night time work is probably undertaken on higher volume roads that have more crashes.

Ullman et al. (2008) conducted a detailed study of safety at daytime and nighttime work zones using data from five States: New York, North Carolina, Ohio, Washington, and California (*55*). New York has a unique database of work zone crashes that provide detailed information about the work zone situation at the time of the crash (e.g., flagging, lane closure, mobile operation, etc.), type of traffic crash, and type of worker construction crash. Data from work zones crashes that occurred from 2000 to 2005 in New York State were analyzed. In the New York state data, accidents occurring between 6 am and 6 pm were coded as daytime accidents and those from 6 pm to 6 am were coded as nighttime accidents. Following is a summary of the results (*55*):

- "Worker involved crashes at nighttime work zones were significantly more severe than in daytime.
- Rear-end crashes comprise a smaller proportion of work zone traffic crashes at night work zone operations than during daytime operations (49% during day versus 36% at night).
- Crashes involving workers, construction vehicles or equipment, and construction materials and debris comprise a greater percentage of crashes at night than during the day.
- Intrusion crashes at night work operations are significantly more severe than at daytime work operations".

The results from the analysis of the other four States from this study are discussed below under 'Freeways; Expressways'.

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

Graham et al.'s 1977 study found that daytime accidents increased by about 8%, and nighttime accidents increased by about 9% compared to before construction (mixed urban and rural settings, all road types, all accident types and severities) (page 36) (*24*). The authors pointed out that "the number of night accidents increased during construction, but the proportion of night accidents to total accidents remained the same" (page 83) (*24*). Although this study provides some insight to the accident experience of a work zone during daytime compared to nighttime, no AMFs can be derived.

Freeways; Expressways

Elvik and Vaa's overview of the effects of road safety noted that a 1985 English study of freeways "showed that accidents during road works increase on a percentage basis more with work at night than with work during the day. The increase was least where the road works site was not illuminated" (page 453) (*14*). Elvik and Vaa did not derive AMFs.

Ullman et al. (2008) used the empirical Bayes before-during method to examine the safety of daytime and nighttime construction zones with and without temporary lane closures (*55*). The analysis focused on a total of 64 construction projects on freeway sections encompassing about 465 centerline-miles of roadway and a total of over 82 years of work. The average length of a construction project was 7 miles and the average duration was 16 months. Exhibits 6-17 through 6-19 show the expected change in crashes (in the form of an index of change) that occurs when a construction zone is introduced. In these exhibits, day is defined from 6 am to 7 pm, and night is from 7 pm to 6 am. Results for three conditions are shown: active work with temporary lane closure, active work with no temporary lane closure, and no active work and no temporary lane closure. This study was rated High and a MCF of 1.2 was applied to the standard errors.

Exhibit 6-17 shows the expected changes in crashes when there was active work with temporary lane closures. Results are provided for three AADT ranges (< 50,000; 50,000-100,000; > 100,000) and also for all AADT ranges combined. Day time lane closures were more common at the lower AADT levels while night time lane closures were more common at higher AADT levels. Subtracting 1 from the index of change and expressing it as a percent will give the percentage increase in crashes that will occur. Looking at the results for all the AADT ranges combined, the index of change for day and night time crashes is quite similar. However, since the number of crashes is typically much higher during the day compared to night, daytime lane closures would lead to a much larger increase in crashes.

Exhibit 6-17: Safety impacts of daytime and nighttime work zones in freeways (active work with temporary lane closure)(55)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
Ullman et al., 2008	Active work with temporary lane closure	Night	Freeway, AADT < 50,000	Injury accidents; all types	1.318	0.272
	Active work with temporary lane closure	Day	Freeway, AADT < 50,000	Injury accidents; all types	1.596	0.179
	Active work with temporary lane closure	Night	Freeway, AADT 50,000-100,000	Injury accidents; all types	1.335	0.181
	Active work with temporary lane closure	Day	Freeway, AADT 50,000-100,000	Injury accidents; all types	1.116	0.293

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	Active work with temporary lane closure	Night	Freeway, AADT > 100,000	Injury accidents; all types	1.491	0.139
	Active work with temporary lane closure	Day	Freeway, AADT > 100,000	Injury accidents; all types	1.261	0.269
	Active work with temporary lane closure	Night	Freeway, All AADT ranges	Injury accidents; all types	1.423	0.102
	Active work with temporary lane closure	Day	Freeway, All AADT ranges	Injury accidents; all types	1.455	0.134
	Active work with temporary lane closure	Night	Freeway, AADT < 50,000	PDO accidents; all types	1.630	0.226
	Active work with temporary lane closure	Day	Freeway, AADT < 50,000	PDO accidents; all types	1.899	0.151
	Active work with temporary lane closure	Night	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.712	0.164
	Active work with temporary lane closure	Day	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.338	0.256
	Active work with temporary lane closure	Night	Freeway, AADT > 100,000	PDO accidents; all types	1.798	0.124
	Active work with temporary lane closure	Day	Freeway, AADT > 100,000	PDO accidents; all types	1.870	0.239
	Active work with temporary lane closure	Night	Freeway, All AADT ranges	PDO accidents; all types	1.748	0.091
	Active work with temporary lane closure	Day	Freeway, All AADT ranges	PDO accidents; all types	1.808	0.115
	Active work with temporary lane closure	Night	Freeway, AADT < 50,000	All accidents; all types	1.527	0.176
	Active work with temporary lane closure	Day	Freeway, AADT < 50,000	All accidents; all types	1.770	0.115
	Active work with temporary lane closure	Night	Freeway, AADT 50,000-100,000	All accidents; all types	1.569	0.124

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	Active work with temporary lane closure	Day	Freeway, AADT 50,000-100,000	All accidents; all types	1.262	0.193
	Active work with temporary lane closure	Night	Freeway, AADT > 100,000	All accidents; all types	1.649	0.091
	Active work with temporary lane closure	Day	Freeway, AADT > 100,000	All accidents; all types	1.645	0.180
	Active work with temporary lane closure	Night	Freeway, All AADT ranges	All accidents; all types	1.609	0.068
	Active work with temporary lane closure	Day	Freeway, All AADT ranges	All accidents; all types	1.663	0.088

Exhibit 6-18: Safety impacts of daytime and nighttime work zones in freeways (active work with no temporary lane closure) (55)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
Ullman et al., 2008	Active work with no temporary lane closure	Night	Freeway, AADT < 50,000	Injury accidents; all types	2.256	1.562
	Active work with no temporary lane closure	Day	Freeway, AADT < 50,000	Injury accidents; all types	1.452	0.259
	Active work with no temporary lane closure	Night	Freeway, AADT 50,000-100,000	Injury accidents; all types	1.341	0.406
	Active work with no temporary lane closure	Day	Freeway, AADT 50,000-100,000	Injury accidents; all types	1.189	0.074
	Active work with no temporary lane closure	Night	Freeway, AADT > 100,000	Injury accidents; all types	1.395	0.382
	Active work with no temporary lane closure	Day	Freeway, AADT > 100,000	Injury accidents; all types	1.132	0.068

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	Active work with no temporary lane closure	Night	Freeway, All AADT ranges	Injury accidents; all types	1.414	0.275
	Active work with no temporary lane closure	Day	Freeway, All AADT ranges	Injury accidents; all types	1.174	0.050
	Active work with no temporary lane closure	Night	Freeway, AADT < 50,000	PDO accidents; all types	1.359	0.816
	Active work with no temporary lane closure	Day	Freeway, AADT < 50,000	PDO accidents; all types	1.371	0.176
	Active work with no temporary lane closure	Night	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.227	0.304
	Active work with no temporary lane closure	Day	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.410	0.067
	Active work with no temporary lane closure	Night	Freeway, AADT > 100,000	PDO accidents; all types	2.037	0.352
	Active work with no temporary lane closure	Day	Freeway, AADT > 100,000	PDO accidents; all types	1.388	0.053
	Active work with no temporary lane closure	Night	Freeway, All AADT ranges	PDO accidents; all types	1.666	0.229
	Active work with no temporary lane closure	Day	Freeway, All AADT ranges	PDO accidents; all types	1.398	0.041
	Active work with no temporary lane closure	Night	Freeway, AADT < 50,000	All accidents; all types	1.642	0.746
	Active work with no temporary lane closure	Day	Freeway, AADT < 50,000	All accidents; all types	1.386	0.145

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	Active work with no temporary lane closure	Night	Freeway, AADT 50,000-100,000	All accidents; all types	1.285	0.246
	Active work with no temporary lane closure	Day	Freeway, AADT 50,000-100,000	All accidents; all types	1.323	0.050
	Active work with no temporary lane closure	Night	Freeway, AADT > 100,000	All accidents; all types	1.797	0.258
	Active work with no temporary lane closure	Day	Freeway, AADT > 100,000	All accidents; all types	1.299	0.042
	Active work with no temporary lane closure	Night	Freeway, All AADT ranges	All accidents; all types	1.577	0.178
	Active work with no temporary lane closure	Day	Freeway, All AADT ranges	All accidents; all types	1.314	0.032

Exhibit 6-19: Safety impacts of daytime and nighttime work zones in freeways (no active work and no temporary lane closure) (55)

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
Ullman et al., 2008	No active work and no temporary lane closure	Night	Freeway, AADT < 50,000	Injury accidents; all types	1.054	0.104
	No active work and no temporary lane closure	Day	Freeway, AADT < 50,000	Injury accidents; all types	1.106	0.073
	No active work and no temporary lane closure	Night	Freeway, AADT 50,000-100,000	Injury accidents; all types	1.141	0.085
	No active work and no temporary lane closure	Day	Freeway, AADT 50,000-100,000	Injury accidents; all types	0.936	0.046

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	No active work and no temporary lane closure	Night	Freeway, AADT > 100,000	Injury accidents; all types	1.106	0.076
	No active work and no temporary lane closure	Day	Freeway, AADT > 100,000	Injury accidents; all types	1.051	0.036
	No active work and no temporary lane closure	Night	Freeway, All AADT ranges	Injury accidents; all types	1.114	0.050
	No active work and no temporary lane closure	Day	Freeway, All AADT ranges	Injury accidents; all types	1.020	0.026
	No active work and no temporary lane closure	Night	Freeway, AADT < 50,000	PDO accidents; all types	1.133	0.082
	No active work and no temporary lane closure	Day	Freeway, AADT < 50,000	PDO accidents; all types	1.271	0.060
	No active work and no temporary lane closure	Night	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.309	0.080
	No active work and no temporary lane closure	Day	Freeway, AADT 50,000-100,000	PDO accidents; all types	1.102	0.040
	No active work and no temporary lane closure	Night	Freeway, AADT > 100,000	PDO accidents; all types	1.455	0.071
	No active work and no temporary lane closure	Day	Freeway, AADT > 100,000	PDO accidents; all types	1.234	0.030
	No active work and no temporary lane closure	Night	Freeway, All AADT ranges	PDO accidents; all types	1.330	0.047
	No active work and no temporary lane closure	Day	Freeway, All AADT ranges	PDO accidents; all types	1.196	0.022

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
	No active work and no temporary lane closure	Night	Freeway, AADT < 50,000	All accidents; all types	1.094	0.065
	No active work and no temporary lane closure	Day	Freeway, AADT < 50,000	All accidents; all types	1.208	0.047
	No active work and no temporary lane closure	Night	Freeway, AADT 50,000-100,000	All accidents; all types	1.240	0.061
	No active work and no temporary lane closure	Day	Freeway, AADT 50,000-100,000	All accidents; all types	1.042	0.030
	No active work and no temporary lane closure	Night	Freeway, AADT > 100,000	All accidents; all types	1.303	0.052
	No active work and no temporary lane closure	Day	Freeway, AADT > 100,000	All accidents; all types	1.159	0.023
	No active work and no temporary lane closure	Night	Freeway, All AADT ranges	All accidents; all types	1.237	0.035
	No active work and no temporary lane closure	Day	Freeway, All AADT ranges	All accidents; all types	1.127	0.017

A recent FHWA report provides average crash costs for twenty two different crash types (*59*). Based on information from that report, the average cost for PDO crashes on freeways = $7,800, and the average cost for injury and fatal crashes = $206,015. Using these crash costs, information from Exhibits 6-17 through 6-19, and average crashes per mile on California freeways, Exhibits 20 through 22 show graphs between increased crash costs per 100 work-hours per mile of work and AADT (similar trends will be obtained if crash frequencies from other States are used, although the absolute numbers will be different) (*55*).

It is clear from Exhibit 6-20 that working during the day when work activities require travel lanes to be temporarily closed results in higher crash costs – the difference between day and night increases at higher AADT levels. Exhibit 6-21 indicates that the differences between working at night versus working during the day on tasks that do not require lane closure are less clear. The increased crash costs are very close for night and day. In situations where work is inactive and there is no lane closure the increased crash costs are slightly higher at night (Exhibit 6-22), but increased costs are lower across the entire range of AADT when compared to situations when there is active work.

Exhibit 6-20: Relationship between increased crash costs and freeway AADT (active work with temporary lane closure) (55)

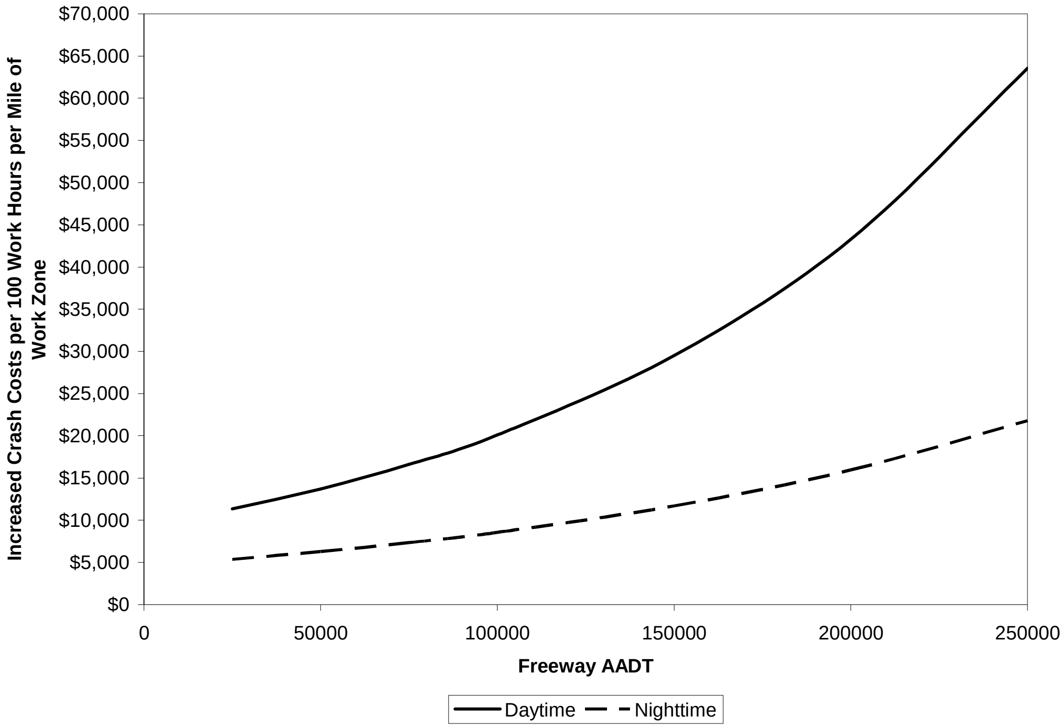


Exhibit 6-21: Relationship between increased crash costs and freeway AADT (active work without temporary lane closure) (55)

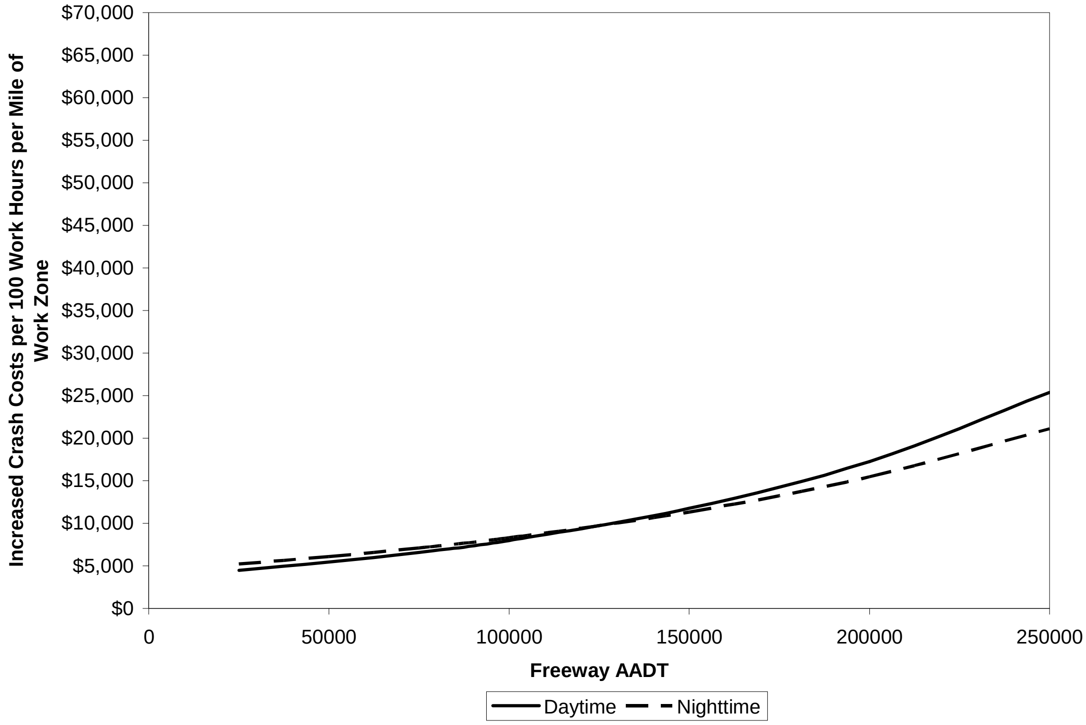
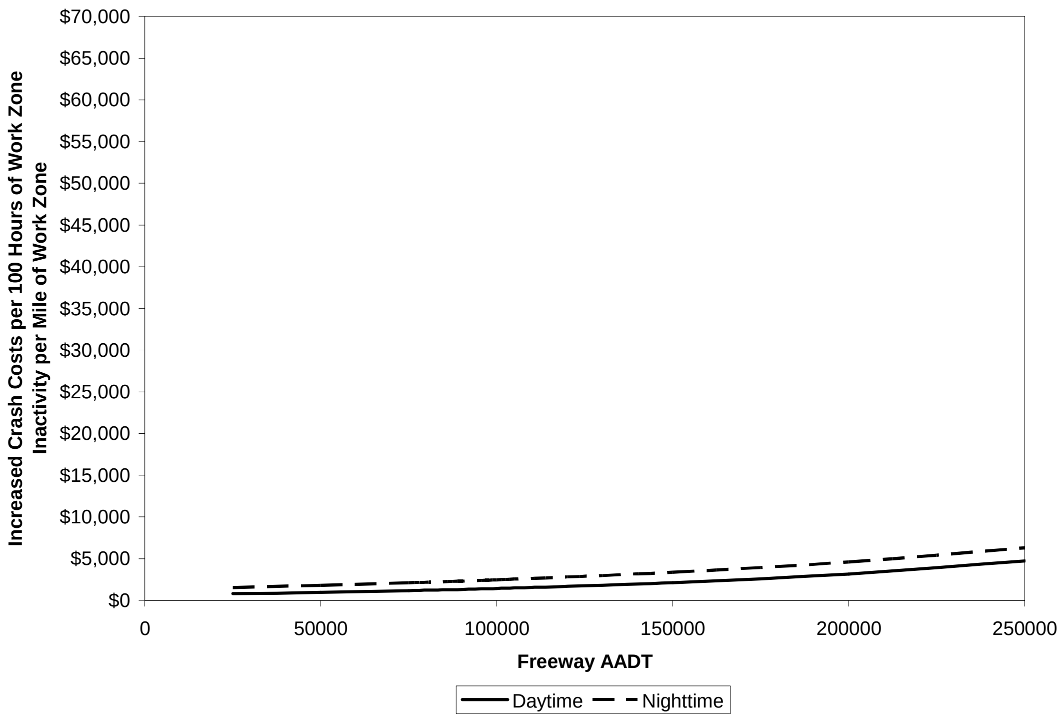


Exhibit 6-22: Relationship between increased crash costs and freeway AADT (no active work and temporary lane closure) (55)



Discussion: Construction stages

Rural two-lane roads; Rural multi-lane highways; Urban and suburban arterials

No studies found.

Freeways; Expressways

Based on a study on urban freeways in Chicago, Rouphail et al. (1990) commented that accident risk "is at its highest during the initial construction stage" (page 138) (*22*). They noted that drivers experienced many difficulties adapting to the new conditions in the very early stage of a work zone and considered this period to be particularly vulnerable. Rouphail et al. concluded that "by far the largest discriminant of accident rates" was the construction stage itself (page 139) (*22*). In the early stages ("at or shortly after the start of the construction activities" (page 139) (*22*)), the average accident rate was 9.71 accidents/million-vehicle-miles (acc/mvm) compared with 6.00 acc/mvm in the later stages. The researchers comment that these results suggest that drivers might have had challenges adapting to the new traffic control procedures and the new geometric constraints. However, AMFs could not be determined from this study.

No studies were found for rural freeways.

6.2.1.2. Lane Closure Design

There are two main alternative types of lane closure design for work zones on freeways, rural multi-lane roadways, and urban and suburban arterials:

- Crossover closure with two-lane two-way operations (TLTWO); and
- Single (or partial) lane closure in one direction.

This section examines the safety effects of crossover closures and single lane closures at a work zone.

In **crossover closures**, all the lanes in one direction of a divided or undivided multi-lane highway are closed (Exhibit 6-23). For example, if construction is taking place on the northbound lanes, all the northbound lanes are closed, but the southbound lanes remain open and are used for both directions of traffic. Traffic on the northbound lanes must “cross over” the median or centerline to travel on the southbound lanes. Once on the southbound lanes, the northbound and southbound traffic face each other without a median. This is known as two-lane two-way traffic operations (TLTWO).

The TLTWO roadway is signed and marked for two-way traffic. Temporary centerlines or other dividers may be used to separate the traffic (Section 6.2.1.3). Using this closure type, work crews are able to work without nearby traffic, however, heavy traffic volumes, loaded trucks, nighttime and bad weather can create safety concerns with respect to the two-way two-lane temporary arrangement.

Median crossover design varies for the crossover closures. The two main categories described by Graham and Migletz are flat diagonal designs and reverse curve designs (*25*). Flat diagonal designs are constructed with no superelevation or curvature in the crossover. Reverse curve designs employ two curves in the crossover and frequently have superelevation in the curves.

In **single lane closures**, full closure of all the lanes in one direction at any one time does not occur (Exhibit 6-24). Although defined as “single lane closures”, one or more lanes may be closed at any one time. The number of lanes closed depends on the total number of lanes on the roadway and the construction circumstances.

A work zone using a single lane closure does not directly affect traffic on the non-construction side of the roadway. Traffic on the construction side passes close to or adjacent to the work zone and work crew.

This section discusses the safety impact of crossover closures and single lane closures at work zones on multi-lane roads.

However, available information is limited and there is a need to better quantify the safety impact of the following:

- Work zones with crossover closures on rural and urban multi-lane roads and freeways for all accident types and severities for different traffic conditions;
- Work zones with single lane closures on rural and urban multi-lane roads and freeways for all accident types and severities for different traffic conditions;
- Different median crossover designs used in crossover closures;
- Different lane closure design elements such as taper lengths and lane widths; and
- Lane closure design for two-lane roads.

The safety effects of closing the right hand lanes vs. closing the left hand lanes, and centerline treatments used to separate opposing traffic are discussed in Section 6.2.1. Lane markings and delineation (cones, markings, etc.) for lane closure design are discussed in Section 6.2.2.

Exhibit 6-23: Crossover closure with two-lane two-way operation (25)

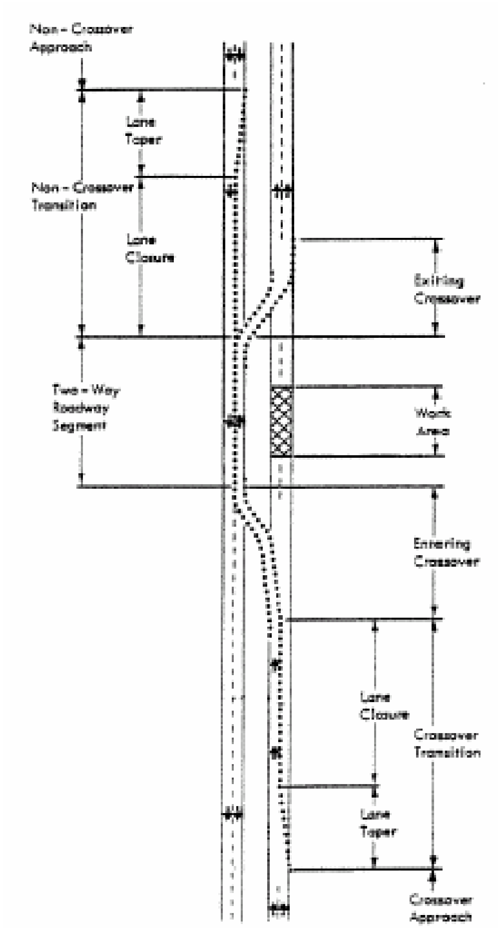


Exhibit 6-24: Single lane closure (24)

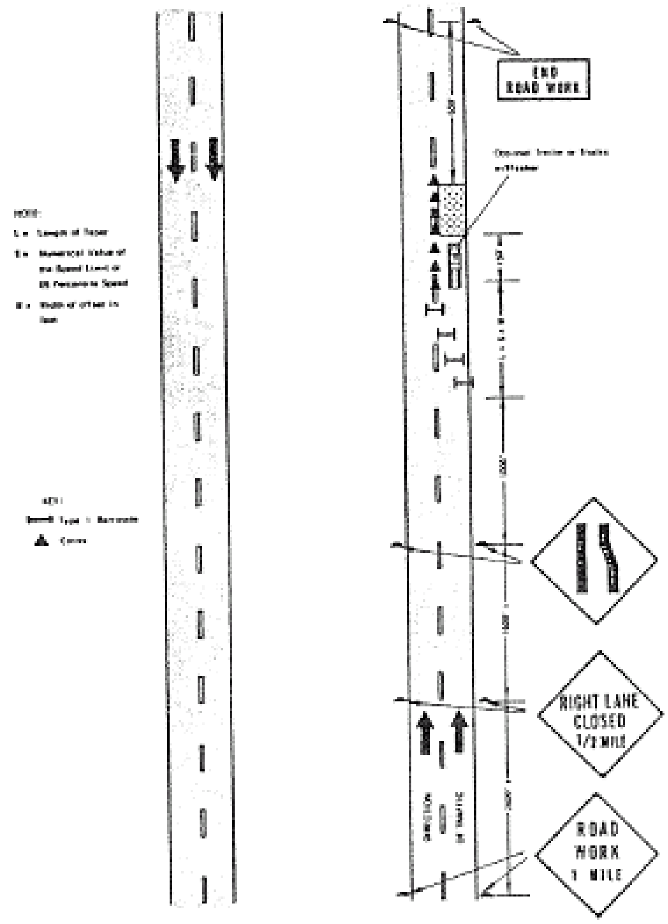


Exhibit 6-25: Resources used to investigate the safety effect of lane closure design in work zones

DOCUMENT	DESCRIPTION	COMMENT
(Tarko, A. P. and Venugopal, S., "Safety and Capacity Evaluation of the Indiana Lane Merge System Final Report." FHWA/IN/JTRP-2000/19, West Lafayette, Ind., Purdue University, (2001))	The study evaluated the Indiana Lane Merge System (ILMS) which is an advanced dynamic traffic control system designed to encourage drivers to switch lanes well in advance of the work zone entry taper.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Pesti, G., Jessen, D. R., Byrd, P. S., and McCoy, P. T., "Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999))	The reports evaluated a late merge system. Conflicts were used as a surrogate for safety.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(*26*) (Pal, R. and Sinha, K. C., "Analysis of Crash Rates at Interstate Work Zones in Indiana." Transportation Research Record 1529, Washington, D.C., Transportation Research Board, National Research Council, (1996) pp. 43-53.)	The authors used a before and after study with a comparison group to analyze the relative safety of crossover lane closures (two-way traffic operations) and partial lane closures.	Reference suggested by NCHRP 17-18(4). Added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Rouphail, N. M., Yang, Z. S., and Fazio, J., "Comparative Study of Short- and Long-Term Urban Freeway Work Zones." Transportation Research Record 1163, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 4-13.)	The study compared the accident experience of four long-term and 23 short-term projects before, during and after urban freeway work zones between 1981 and 1983.	Study not concerned with lane closure design. Not added to synthesis.
(*27*) (Dudek, C. L., Richards, S. H., and Buffington, J. L., "Some Effects of Traffic Control on Four-Lane Divided Highways." Transportation Research Record 1086, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 20-30.)	The study evaluated single lane closures in one direction, and crossover closures with two-lane two-way operations (TLTWO) at nine sites.	Reference suggested by NCHRP 17-18(4). Added to synthesis.
(*25*) (Graham, J. L. and Migletz, J., "Design Considerations for Two-Lane, Two-Way Work Zone Operations." FHWA/RD-83/112, Washington, D.C., Federal Highway Administration, (1983))	The study investigated the safety and operational problems of 22 TLTWO sites and compared the results with 14 lane closure sites.	Reference suggested by NCHRP 17-18(4). Added to synthesis.
(Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	The study analyzed accidents that occurred before and during construction in 79 zones in seven states in the 1970s.	Reference suggested by NCHRP 17-18(4). Added to Section 6.2.1.1.

Most of the crossover closures and single lane closures study results relate to rural multi-lane divided highways and all accident types and severities, and compare the work zone conditions to the no-work zone condition. Although some studies did not clearly specify the setting, few studies appeared to investigate urban crossover or urban single lane closures. Traffic volumes were not usually specifically mentioned in the studies. All the studies except one express their findings as accident rates rather than as accident frequencies. Some studies present amalgamated results and others present results site by site.

Treatment: Use crossover closure at work zone

Rural two-lane roads

Not applicable.

Rural multi-lane highways; Freeways; Expressways

Three studies provided estimates of the effect of crossover closures on accidents in work zones on rural multi-lane highways and freeways. The results are shown in Exhibit 6-26, comparing the accident experience during construction to before construction. These results contain mixed site types, including rural combined with suburban, and multi-lane highways combined with freeways. The studies also included a variety of centerline treatments and crossover designs (location, length, curves, signing, use of temporary barriers, quality of road surface, etc.).

Accidents during a crossover closure usually increased compared with the before work zone period. As shown in Exhibit 6-26, the Dudek et al. study showed no change over three sites combined, but increases in the other two studies ranged from 7% to 61% for all accident types and all severities.

The index of effectiveness of 1.00 (s = 0.35) for the Dudek study (Exhibit 6-26) is based on three sites (*27*), and was calculated by using accident rate data supplied by Dudek et al. and by assuming that the number of accidents that occurred in the construction periods (which ranged from 1.2 to 10.6 months) was proportional to the number of accidents that would have occurred during a whole year. Only one year of before data was provided. Sufficient information was available to calculate s ideal from the Dudek et al. study, using Eqn 7.3 from Hauer (*28*). A method correction factor of 3 was applied, reflecting the limited number of sites, data used in the study, and the methodology applied, yielding an s value of 0.35.

Pal and Sinha included data accident severity in their study and found marked increases in both injury and fatal accidents during a crossover closure compared to before construction: the index of effectiveness for injury and fatal accidents was 1.84 on four-lane divided roadways and 1.66 on six-lane divided roadways (*26*). The estimate of the standard error is unknown

Pal and Sinha analyzed the safety of crossover lane closures (two-way traffic operations) at 4R projects (resurfacing, restoration, rehabilitation and reconstruction) in Indiana (*26*). Pal and Sinha's study was based on a before and during study with a comparison group and a non-Bayesian approach. They did not use the empirical Bayes approach in their study "because of the sparsity of data" (page 44). No accident frequencies were provided in the publication. The study also included regression models to evaluate the relative safety effects of any future lane closure strategy at a given site, but the authors concluded that the results were limited by the size of the data set (*26*).

Note that the Pal and Sinha's data (Exhibit 6-26) are taken from the authors' averages based on 13 crossover work zone sites. The "during work zone" accident rate was divided by the "before work zone" accident rate to produce the index of effectiveness. Pal and Sinha base the "before work zone" accident rates on similar time periods during the five years preceding the work zones (*26*).

Graham and Migletz conducted a detailed study of the safety and operational problems of TLTWO at 22 work zones sites in 1981 (*25*). The study was conducted in response to controversy regarding TLTWO due to the possibility of head-on accident problems in the two-way portion of the zone. Most of the sites were on interstate roadways. Volumes and setting were not reported.

Graham and Migletz calculated accident rates (per 100 MVM) for those sites where before and during construction data were available. Graham and Migletz found that accident rates increased by 7% at the TLTWO sites compared with the time before the work zone (Exhibit 6-26) (*25*). This increase appears to represent all accident types and severities in the work zone. A standard error for this value was unavailable.

Exhibit 6-26: Estimates of the effect of crossover closures on accident rates in work zones compared to before construction

Author, date	**Treatment /element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Pal and Sinha, 1996	TLTWO	Not specified	Four-lane divided, volume not reported	All types, all severities	1.33	Not available
Dudek et al 1986	TLTWO	Not specified	Four-lane divided, 6,800 to 38,000 veh/day	All types, all severities	1.00	0.35

Author, date	Treatment /element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Pal and Sinha, 1996	TLTWO	Not specified	Six-lane divided, volume not reported	All types, all severities	1.61	Not available
Graham and Migletz 1983	TLTWO	Almost all rural (few suburban)	Multi-lane divided, volume not reported	All types, all severities	1.07	Not available
Pal and Sinha, 1996	TLTWO	Not specified	Four-lane divided, volume not reported	All types, Injury and fatal	1.84	Not available
Pal and Sinha, 1996	TLTWO	Not specified	Six-lane divided, volume not reported	All types, Injury and fatal	1.66	Not available

In summary, at crossover closures, the increase for all accident types and severities ranged from no change to about a 60% increase. When considering accident severity of injury and fatal, accidents may increase from 66 to 84% after a crossover work zone is implemented. However, standard errors could not be developed based on the available studies.

Discussion: Using a crossover closure in a work zone (Rural multi-lane highways; Freeways; Expressways

Graham and Migletz note that severe accidents (including head-on accidents) tended to occur in the TLTWO zone. “The two-way segment had the largest number of accidents of any part of the TLTWO zone and also the greatest severity” (page 66), but “There were not a great number of severe head-on accidents in the TLTWO zones” (page 66). Graham and Migletz noted that drivers who were traveling in the non-crossover direction (and who did not have to cross the median to enter the TLTWO) were most “at fault” (page 7). “Such drivers are less likely to be aware of the two-way operation because they may not have had to change lanes or change their path to enter the work zone” (page 7) (*25*).

Graham and Migletz also noted that pavement and shoulder conditions are important in the TLTWO zone, especially the two-way roadway segment (*25*).

Graham and Migletz gave detailed attention to crossover medians and crossover median design; however, no AMFs were obtainable from their publication. Compared with the two-way segment of the TLTWO design, the less severe accidents tended to occur in the crossover median areas (*25*). The Graham and Migletz study included case studies of six TLTWO sites and detailed comments on crossover design. The “entering crossover” areas experienced more accidents than did the “exiting crossovers”. “There were 60% more accidents at entering crossovers than at exiting crossovers” (page 66). Graham and Migletz report that provision for loaded trucks was the most critical aspect of crossover design; fixed object accidents were the most common and often involved portable concrete barriers where these were used. Rear-end accidents were the second most common accident type (*25*).

Flat diagonal entering and exiting crossover designs “had a much lower accident rate” than reverse curve designs (page 66). Accident rates at the entering crossovers were lower when the right approach lane was closed than when the left approach lane was closed. No AMFs could be derived.

Urban and suburban arterials

No studies were found.

Treatment: Use single lane closure at work zone

Rural two-lane roads

Not applicable.

Rural multi-lane highways; Freeways; Expressways

The same three studies used in the crossover closure summary provided estimates of the effect of single lane closures on accidents in work zones. Four estimates of the effect of single lane closures on all accident types and all severities in work zones are shown in Exhibit 6-27. The results show that accidents increased during a single lane closure from 33% to 90%.

Pal and Sinha included data accident severity in their study (*26*). They found a marked increase in both injury and fatal accidents during a crossover closure: the index of effectiveness for injury and fatal accidents was 1.85 on four-lane divided roadways and 1.20 on six-lane divided roadways (Exhibit 6-27). The estimate of the standard error is not known.

Pal and Sinha analyzed the safety of single lane closures (two-way traffic operations) at 4R projects (resurfacing, restoration, rehabilitation and reconstruction) in Indiana (*26*). Pal and Sinha's study was based on a before and during study with a comparison group and a non-Bayesian approach. Pal and Sinha did not to use the empirical Bayes approach in their study "because of the sparsity of data" (page 44). No accident frequencies were provided in the publication. The study also included regression models to evaluate the relative safety effects of any future lane closure strategy at a given site, but the authors concluded that the results were limited by the size of the data set (*26*).

Note that the Pal and Sinha data (Exhibit 6-27) are taken from the authors' averages based on 21 single lane closure projects. The "during work zone" accident rate was divided by the "before work zone" accident rate to produce the index of effectiveness. The authors based their "before work zone" accident rates on the accident rates that occurred over similar time periods during the five years preceding the work zones (*26*).

The index of effectiveness of 1.56 (s = 0.70) (Exhibit 6-27) for the Dudek et al. study is based on four sites (*27*), and was calculated by using accident rate data supplied by Dudek et al. and by assuming that the number of accidents that occurred in the construction periods (which ranged from 1.2 to 10.6 months) was proportional to the number of accidents that would have occurred during a whole year. Only one year of before data was provided. Sufficient information was available to calculate s ideal from the Dudek et al. study, using Eqn 7.3 from Hauer (28). A Method Correction Factor of 3 was applied, reflecting the limited number of sites and data used in the study and the methodology applied, yielding an s value of 0.70.

Although the Graham and Migletz study focused on TLTWO sites, they also commented on single lane closures (*25*). Accidents at the one site for which data are given increased by 190% (Exhibit 6-27) compared with the "before" period (page 46) (*25*). The estimate of the standard error is not known. Due to the lack of detailed supporting data, it is not possible to comment further on the study's quantitative findings. Graham and Migletz reviewed 14 single lane closure sites, and noted that fixed object accidents were the most common type of accident. They also noted that most of the lane closure accidents occurred in the work area, but that the severity of accidents that occurred in the lane closure zone was higher than the severity in the work area.

Exhibit 6-27: Estimates of the effect of single lane closures on accident rates in work zones

Author, date	Treatment/ element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Pal and Sinha, 1996	Single lane closure	Not specified	Four-lane divided, volume not reported	All types, all severities	1.33	Not available
Dudek et al 1986	Single lane closure	Not specified	Four-lane divided, 20,000 to 41,500 veh/day	All types, all severities	1.56	0.70
Pal and Sinha, 1996	Single lane closure	Not specified	Six-lane divided, volume not reported	All types, all severities	1.34	Not available
Graham and Migletz 1983	Single lane closure	Almost all rural (few suburban)	Multi-lane divided, volume not reported	All types, all severities	1.90	Not available
Pal and Sinha, 1996	Single lane closure	Not specified	Four-lane divided, volume not reported	All types, Injury and fatal	1.85	Not available
Pal and Sinha, 1996	Single lane closure	Not specified	Six-lane divided, volume not reported	All types, Injury and fatal	1.20	Not available

In summary, at single lane closures, the increases in crashes ranged from about 33% to about 90% for all severities, including injury and fatal crashes. It is not possible to develop standard errors from the available studies.

Urban and suburban arterials

No studies were found.

Discussion: Comparison of crossover closures and single lane closures

Accidents increased substantially at most work zones with either crossover closures or single lane closures, but it is not clear from the research available whether crossover closures or single lane closures are preferable. Pal and Sinha (*26*) tended to find that accident rates were higher at crossover closures whereas Dudek et al. (*27*) and Graham and Migletz (*25*) tended to find that accident rates were higher at single lane closures. Although Pal and Sinha concluded that crash rates were higher at crossover lane closures than at single lane closures, the difference was small and not statistically significant, "The average work zone crash rate under a crossover strategy was not found to be significantly higher than under a partial lane closure strategy", (page 52) (*26*) but "There is some evidence that there may be a greater chance of having a severe crash in a crossover than in a partial closure" (page 45) (*26*).

The results are summarized in Exhibit 6-28 (all accident types and severities) and Exhibit 6-29 (fatal and injury accidents).

Exhibit 6-28: Comparison of estimates of the effect of crossover closures vs. single lane closures on accident rates (all types and severity) in work zones

Author, date	Setting	Road type	Volume	Crossover closures Index of Effectiveness, $t_{adjusted}$	Single lane closures Index of Effectiveness, $t_{adjusted}$
Pal and Sinha, 1996	Not specified	Four- lane divided	Not specified	1.33	1.33
Dudek et al 1986	Not specified	Four- lane divided	6,800 – 41,500	1.00	1.56
Pal and Sinha, 1996	Not specified	Six- lane divided	Not specified	1.61	1.34
Graham and Migletz 1983	Almost all rural (few suburban)	Multi-lane divided	Not specified for all sites	1.07	1.90

Exhibit 6-29: Comparison of estimates of the effect of crossover closures vs. single lane closures on accident rates (all types, fatal and injury) in work zones

Author, date	Setting	Road type	Volume	Crossover closures Index of Effectiveness, $t_{adjusted}$	Single lane closures Index of Effectiveness, $t_{adjusted}$
Pal and Sinha, 1996	Not specified	Four- lane divided	Not specified	1.84	1.85
Pal and Sinha, 1996	Not specified	Six- lane divided	Not specified	1.66	1.20

6.2.1.3. Lane Closure Merge Design

At many work zones, it is necessary to close one or more lanes. Therefore, vehicles must merge into the lanes available. This section of the manual examines the safety effect of different lane merge systems used in work zones. The transition area at the beginning of a work zones requires drivers to adapt their driving behavior to the new and possibly unexpected conditions ahead. Each driver must modify his/her speed and lane positioning, interacting with the other drivers at the site. The safety of the location will depend on the success of drivers' adaptations.

The safety of lane merge systems used in work zones may be affected by the location of the work zone relative to interchange ramps and roadway intersections.

Studies of two types of lane closure merge designs were found in the literature: the Indiana Lane Merge System (ILMS) and the Late Merge. Some discussion of the safety effects of closing the right lane(s) vs. closing the left lane(s), and of interchange ramps and roadway intersections located close to work zone lane merges is included in this section.

However, currently available information is qualitative and tentative. There is a need to quantify the safety impact of the all of the elements involved in lane merge decisions.

Lane markings and delineation in work zones are discussed in Section 6.2.2.

Exhibit 6-30: Resources used to investigate the safety effect of lane closure merge design in work zones

DOCUMENT	DESCRIPTION	COMMENT
(*21*) (Tarko, A. P. and Venugopal, S., "Safety and Capacity Evaluation of the Indiana Lane Merge System Final Report." FHWA/IN/JTRP-2000/19, West Lafayette, Ind., Purdue University, (2001))	The study evaluated the Indiana Lane Merge System (ILMS) using procedures that combined crash-based and conflict-based crash prediction models to evaluate the safety effects of the ILMS in a real construction zone.	Reference suggested by NCHRP 17-18(4). Limited qualitative information. Added to the synthesis. No AMFs.
(*29*) (Pesti, G., Jessen, D. R., Byrd, P. S., and McCoy, P. T., "Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999))	The paper evaluated the operational effects of the Late Merge concept in reducing queues and road rage at work zones. The study used traffic conflicts as a measure of safety effectiveness.	Reference suggested by NCHRP 17-18(4). Limited qualitative information. Added to the synthesis. No AMFs.
(*22*) (Rouphail, N. M., Mousa, R., Said, K., and Jovanis, P. P., "Freeway Construction Zones in Illinois: A Follow-Up Study. Final Report." FHWA/IL/RC-004, Springfield, Illinois Department of Transportation, (1990))	The study includes a very detailed investigation of three major work zones on an urban freeway in Chicago over a four-year period before, during and after construction.	Limited qualitative information. Added to the synthesis. No AMFs.
(*23*) (Rouphail, N. M., Yang, Z. S., and Fazio, J., "Comparative Study of Short-and Long-Term Urban Freeway Work Zones." Transportation Research Record 1163, Washington, D.C., Transportation Research Board, National Research Council, (1988) pp. 4-13.)	The study compared the accident experience of three long-term (longer than four days) and 23 short-term sites before, during and after freeway construction or maintenance work undertaken between 1981 and 1983.	Added to the synthesis. No AMFs.
(*27*) (Dudek, C. L., Richards, S. H., and Buffington, J. L., "Some Effects of Traffic Control on Four-Lane Divided Highways." Transportation Research Record 1086, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 20-30.)	The study evaluated single lane closures in one direction, and crossover closures with two-lane two-way operations (TLTWO) at nine sites. The study included an investigation of conflicts at merges and right lane vs. left lane closures.	Reference suggested by NCHRP 17-18(4). Limited qualitative information. Added to the synthesis. No AMFs.
(*25*) (Graham, J. L. and Migletz, J., "Design Considerations for Two-Lane, Two-Way Work Zone Operations." FHWA/RD-83/112, Washington, D.C., Federal Highway Administration, (1983))	The study investigated the safety and operations of 22 TLTWO sites and compared the results with 14 lane closure sites.	Added to the synthesis. No AMFs.

Unfortunately, very few accident studies of lane merging at work zones were found. Studies that investigated the safety of lane merging before work zones and the relative location of ramps and intersections often used conflicts during lane merging rather than accidents as the measure. No study provided AMFs.

Discussion: Use Indiana Lane Merge System (ILMS)

Tarko et al. evaluated the Indiana Lane Merge System (ILMS) which is an advanced dynamic traffic control system designed to encourage drivers to switch lanes well in advance of the work zone lane drop and entry taper (*21*). The study used capacity models and crash prediction models to evaluate the safety and capacity effects of the ILMS on four-lane divided rural freeways. A new method that combined crash-based and conflict-based procedures was developed. A value for the relative change in the number of conflicts with and without the system was first established and then assumed by Tarko et al. to be equivalent to the relative change in the number of crashes. This value was multiplied by the number of crashes expected to occur without the system to obtain the expected crash reduction using the new system by Tarko et al. Crash prediction models without ILMS and conflict models with and without ILMS were developed. In addition, a capacity evaluation was conducted to estimate the capacity impacts of ILMS (*21*).

The model showed "positive" safety impacts such as fewer conflicts on merging, with even greater benefits in the form of reduction in trip delay. Tarko et al. note that the system "does not cause any impact until AADT values reach 42,000 veh/day" (page 137) (*21*). The authors comment that since vehicles may be re-routed to avoid the work zone, the safety impact on the surrounding roads should also be considered (*21*).

No AMFs could be derived from this study.

Discussion: Use the Late Merge concept

Pesti et al. (1999) conducted a study of the operational impact of the Late Merge concept in reducing queues and road rage at congested work zones on rural interstates and rural four-lane freeways. The study used traffic conflicts (forced merges into the single open lane, lane straddles and lane blocking) as a measure of safety effectiveness (*29*).

The researchers concluded that although the Late Merge concept would reduce queue length and driver frustration, the "merging operation of vehicles in advance of the work zone was often controlled rather by truck drivers than by the work zone control plan"…."thus the potential benefits of the Late Merge will not be realized unless drivers, particularly truck drivers, have a better understanding and acceptance of the concept' (page 7) (*29*).

No AMFs could be derived from this study.

Discussion: Right lane vs. left lane closures

Dudek et al. considered the safety effects of closing the right lane(s) vs. closing the left lane(s) on four-lane divided highways (*27*). Dudek et al. noted that where volumes are heavy, drivers try to leave the lane that is about to be closed early to avoid being trapped in the taper (*27*). The researchers included an evaluation of conflicts at work zones as an indirect measure of work zone safety. They found that there were fewer conflicts when the right side of the roadway remained open to traffic and the left lanes were closed. In other words, closing the left lane led to fewer conflicts than closing the right lane. "Conflicts occur more frequently at right lane closures [than at left lane closures] probably for two reasons: (a) right lane volumes on a four-lane freeway are usually higher than left lane volumes under light-to-moderate-flow conditions, and (b) drivers are apparently more hesitant to vacate a closed right lane, possibly because they fear missing their downstream ramp" (page 28) (*27*). "No conclusions, however, could be reached from the data regarding the relative safety of right or left lane closures" (page 29) (*27*).

No AMFs could be derived from this study. The results may be considered intuitive; however the following study by Rouphail et al. found the opposite.

Dudek et al. suggested that on rural multi-lane highways, left lane closures for work zones might be safer than right lane closures for work zones. However, Rouphail et al.'s study, which took place on urban freeways in Chicago, suggested the opposite (*22*). Rouphail et al. found that accident rates were higher when the left approach lane was closed than when the right approach lane was closed. In other words, closing the left lane led to higher accident rates than closing the right lane: "Although somewhat counterintuitive", the accident rate was higher when construction work took place over the left side of the roadway (7.93 Acc/MVM) leaving the right-lanes open than when it took place over the right side of the roadway (6.43 Acc/MVM) (page ii) (*22*). Rouphail et al. commented that the higher accident rate associated with left side construction and the closure of the left lanes "may be due to the fact that with right side construction, both ramp and mainline traffic are constrained to operate at low speeds due to capacity limitations on the mainline and the geometric limitations of the ramp side (reduced acceleration and deceleration space). With left side construction, ramp traffic (especially on ramp) is free to approach at the desired speed" (page ii) (*22*).

No AMFs could be derived from this study. These results are the opposite of the study by Dudek et al. The different findings could be due to differences in the rural and urban settings of the studies, traffic volumes, differences in driver behavior when merging from the left compared with merging from the right at the sites examined, and to differences in the sites' layouts and their relation to nearby ramps and intersections.

Discussion: Location of the work zone relative to interchange ramps and roadway intersections

As the exact location of accidents was not usually available to the researchers in any of the studies reviewed, it was not always possible for the researchers to be certain whether an accident took place on a ramp, or on the mainline within the acceleration or deceleration lane area, or just before or after the acceleration or deceleration lane. The lack of precise information on accident location and the large number of variations in circumstances and factors such as ramp type and position frustrated the researchers' analysis.

Graham and Migletz discussed intersections in the vicinity of work zones (*25*). Their study was a detailed investigation of 22 TLTWO sites in 1981, mostly on interstate roadways. In the case of three accidents that occurred at the exiting crossover part of a work zone, for example, the researchers noted that these accidents "were probably more associated with the location of the crossovers near intersections than with the actual design of the crossovers" (page 47) (*25*). At one site, a temporary off-ramp in a work zone on a two-way road segment recorded eight accidents. These accidents were attributed to the effect of the design and signing of the temporary off-ramp and also to the presence of pot-holes. No AMFs could be derived from this study.

Tarko et al.'s Indiana Lane Merge System (ILMS) study mentioned ramps (*21*). This study was conducted on four-lane divided rural freeways and included ramps in the capacity models and crash prediction models designed to evaluate the safety and capacity effects of the ILMS. Tarko et al. noted, "The effect of ramps was found to be insignificant for both the work zone segments and the work zone approaches. The exact reason for the insignificance is not known" (page 52) (*21*). No AMFs could be derived from this study.

Rouphail et al. extended their discussion of whether accident rates at work zones were higher when the left approach lane was closed or when the right approach lane was closed to point out that the location of ramps might have affected the accident experience (*22*). Their study took place on urban freeways in Chicago where they were concerned that "the accident problem on the study segments seems to be concentrated in the vicinity of ramps (particularly entrance ramps)" (page 141) (*22*). Although the increase in accidents for both "near entrance ramps" and "near exit ramps" was very pronounced, (as shown in Table 4.2 in the paper) Rouphail et al. could not further analyze their data because the precise location of the accidents was unknown. It was not possible to establish whether accidents that occurred on ramps were affected by work zone activity or whether the accidents would have occurred anyway. Rouphail et al. noted that accidents in the vicinity of ramps were especially noticeable when the two right lanes were closed and weaving problems arose, but they did not give details (*22*).

A slightly earlier study by Rouphail et al. (1988) (also of work zones on urban freeways in Chicago) noted that "The proportion of ramp accidents increased significantly during construction" (page 6) (*23*). The increase was 45% at work zones that were longer than four days, "The predominant accident types were rear-end crashes and ramp-related accidents, especially when the lane closures involved the two right lanes adjacent to the entrance and exit ramps" (page 13) (*23*). Rouphail et al. pointed out that "The effect of closing the right two lanes is dramatically evident in the occurrence of ramp-related accidents" (page 8) (*23*). This is in contrast Rouphail et al.'s conclusion (1990) (*22*) that closing the left lane led to higher accident rates than closing the right lane. Rouphail et al. suspected that traffic control problems arose as certain lanes were opened or closed to traffic. The weaving problems of merging and diverging traffic needed attention on the sites studied, especially as ADT was high (over 100,000 veh/day). In one project, the presence of the work zone meant that traffic entering or leaving the freeway had to cross two lanes of traffic with little room for acceleration or deceleration (*23*).

No AMFs could be derived from the available literature. The influence on safety of nearby ramps on lane merging at urban and rural work zones is unclear. Further examination of ramp accidents in relation to work zones appears to be warranted, but will require the exact location of the accidents and the work zones in order to understand the details of the accidents and their relationship to work zones. At this stage, no conclusion is possible.

6.2.1.4. Other Design Elements [Future Edition]

In future editions of the HSM, additional design elements and their safety impacts may be discussed in this section, such as surface type of roadway in the work zone, drop-off between new and old pavement, road surface condition for through traffic during construction and maintenance, roadside design (clear zone, barriers, protecting hardware), construction access points and truck acceleration and deceleration areas, presence vs. absence of ramps; and condition of ramp access (space for full vs. reduced acceleration / deceleration). Potential resources are listed in Exhibit 6-31.

Exhibit 6-31: Potential resources on the safety effectiveness of other design elements in work zones

DOCUMENT
(Rouphail, N. M., Mousa, R., Said, K., and Jovanis, P. P., "Freeway Construction Zones in Illinois: A Follow-Up Study. Final Report." FHWA/IL/RC-004, Springfield, Illinois Department of Transportation, (1990))

6.2.2. Safety Effects of Work Zone Traffic Control and Operational Elements

Traffic control devices are needed at work zones to inform drivers of temporary conditions, manage driver expectations, and minimize possible driver confusion. A wide range of traffic control devices may be used under a wide range of work zone circumstances. Work zone traffic control and operational elements include traffic control devices; speed control in work zones; delineation, pavement markings and markers. The safety effect of these elements is discussed in the following sections.

6.2.2.1. Signs and Signals

Since work zones often increase driver workload, appropriate and conspicuous devices are needed to convey information to drivers and to alert them to the presence of construction workers and equipment. Traffic control devices are designed to change the behavior of drivers so that drivers slow down, stop, merge or stay in lane as needed. The type of control device(s) used depends on the road class and setting, the work zone layout, the work zone duration, the cost, whether the work zone is static or moving, and institutional constraints (such as whether trained flaggers are available). Combinations of control devices are commonly used.

It is important that drivers are aware of the traffic control devices sufficiently in advance to make the required maneuver and to minimize potential driver confusion. The recent CH2M HILL study (NCHRP Report 500 Volume 19) noted that improved visibility and clarity is “expected to reduce conflicts” (page 27) (*30*).

Traffic control devices include warning and protective measures. The Manual on Uniform Traffic Control Devices (MUTCD) provides guidance on the layout of traffic control devices at work zones (*3*). Elvik (page 448) points out that traffic control at work zones is designed to (*14*):

- Protect road workers and road users;
- Direct traffic through the work zone with minimum delay and inconvenience; and
- Allow an effective progression of the work zone, where applicable.

Traffic control devices include signs used to alert drivers to conditions and speed reductions, flashing arrows used to indicate the need to change lanes, and channelization devices such as barriers, cones and barrels used to direct traffic.

Most studies evaluate the accident rate at a work zone with a given combination of traffic controls and compare the findings with the accident rates before the work zone. Studies have not compared work zones *with* traffic control devices with work zones *without* traffic control devices. This would give a clearer indication of the effect of traffic controls at work zones, but it is not a practical proposition (*14*).

This section provides information on the safety effects of some traffic control devices used in work zones.

Exhibit 6-32: Resources examined on the safety effectiveness of signs and signals in work zones

DOCUMENT	DESCRIPTION	COMMENT
(Kononov, J. and Znamenacek, Z., "Risk Analysis of Freeway Lane Closure During Peak Hour." Washington, D.C., 84th Transportation Research Board Annual Meeting, (2005))	The paper's objective was to create an expert system which would improve the quality of lane closure decisions. The study examined the increased probability of an accident occurring in a work zone.	Not added to synthesis. No AMFs.
(*30*) (CH2M HILL, "NCHRP Report 500 Volume 19: A Guide for Designing Safer Work Zones - DRAFT." Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report examines safety improvements at work zones including engineering practices, enforcement and education. It discusses "expected effectiveness" in general terms. DRAFT	Limited qualitative information. Added to synthesis.
(*14*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	Limited qualitative information. Added to synthesis.
(*31*) (Potts, I., Stutts, J., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP Report 500 Volume 9: A Guide for Addressing Collisions Involving Older Drivers." Washington, D.C., Transportation Research Board, National Research Council, (2004))	The report provides guidance for accommodating the needs of older drivers.	Limited qualitative information. Added to synthesis.
(Fontaine, M. D. and Hawkins, G. H., "Catalog of Effective Treatments to Improve Driver and Worker Safety at Short-Term Work Zones." FHWA/TX-01/1879-3, Austin, Texas Department of Transportation, (2001))	The report catalogs devices for improving driver and worker safety at very short-term work zones. Quantitative information is limited to a few speed reduction details.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Walker, V. and Upchurch, J., "Effective Countermeasures to Reduce Accidents in Work Zones." FHWA-AZ99-467, Phoenix, Department of Civil and Environmental Engineering, Arizona State University, (1999))	The study reviewed work zone countermeasures and selected six for use in Arizona.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(Pesti, G., Jessen, D. R., Byrd, P. S., and McCoy, P. T., "Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy." Washington, D.C., 78th Transportation Research Board Annual Meeting, (1999))	The paper evaluated the operational effects of the Late Merge concept in reducing queues and road rage at work zones. The study used traffic conflicts (forced merges, lane straddles and lane blocking) as a measure of safety effectiveness.	No relevant information. Not added to synthesis.
(*32*) (McCoy, P. T. and Bonneson, J. A., "Work Zone Safety Device Evaluation." SD92-10-F, Pierre, South Dakota Department of Transportation, (1993))	The research evaluated traffic control devices that could improve safety in work zones in South Dakota. The evaluation included driver recognition and comprehension of traffic control.	Limited quantitative information. Added to synthesis.
(Stout, D., Graham, J., Bryant-Fields, B., Migletz, J., Fish, J., and Hanscom, F., "Maintenance Work Zone Safety Devices Development and Evaluation." SHRP-H-371, Washington, D.C., Strategic Highway Research Program, National Research Council, (1993))	The study evaluated 25 prototype work zone safety devices designed to protect work crews at short-term (one to 12 hour duration) work zones.	Not added to synthesis. No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
(*33*) (Garber, N. J. and Woo, T. H., "Effectiveness of Traffic Control Devices in Reducing Accident Rates at Urban Work Zones." Transportation Quarterly, Vol. 45, No. 2, Washington, D.C., Eno Foundation for Transportation Inc., (1991) pp. 259-270.)	The study used regression models to examine the effectiveness of various combinations of traffic control devices in reducing accidents in urban work zones in Virginia.	Reference suggested by NCHRP 17-18(4). Added to synthesis
(Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	The study analyzed accidents that occurred before and during construction in 79 zones in seven states in the 1970s.	Not used in this synthesis. Does not cover topic.

The studies used in the synthesis did not provide comprehensive results and did not provide quantitative information that could be applied to derive AMFs for any treatment. The qualitative information was also limited.

CH2M HILL's recent study found little information on the safety effects of traffic control devices at work zones (*30*). The study does not provide AMFs, but discusses "expected effectiveness" in general terms. Elvik and Vaa reviewed the literature on some work zone traffic control measures, but also found that the safety effects are often unknown (*14*).

Potts et al.'s study addressed ways to reduce crashes and fatalities involving older drivers (*31*). Older drivers are at increased risk when negotiating work zones because work zones often violate driver expectancy. The study provided no data on accidents.

Discussion: Improve visibility and clarity of signs

The CH2M HILL study addressed the problem of signs failing to give drivers warning sufficiently in advance to make the required maneuver (*30*). The study recommended improving the visibility and clarity of signs and markings while avoiding creating additional confusion for drivers. Improved visibility is "expected to reduce conflicts" (page 27) (*30*). No AMFs were available.

Discussion: Use diverging lights display

McCoy and Bonneson evaluated a diverging lights display designed to give approaching drivers the illusion that they were closing in on a convoy of four maintenance and paint striping vehicles (*32*). The display was mounted on the last vehicle. The study site was a moving work zone on a four-lane interstate freeway with ADT of 8,500 veh/day. The diverging lights display was intended to improve driver recognition of a convoy of paint striping vehicles and to encourage drivers to change lanes well in advance. Traffic conflicts were used to measure effectiveness. The diverging lights display "was not effective in improving driver recognition of the paint striping convoy" (page 56) (*32*). Some erratic maneuvers suggested that the display added to driver confusion. No AMFs could be derived.

Discussion: Use various traffic controls at work zones (Traffic signals, Manual traffic control, Flaggers)

Elvik and Vaa found that "The effect on accidents of signals at road works is not known". The authors made no further comment (page 452) (*14*). Elvik and Vaa also found that the effect on accidents of manual traffic control "is not known". The authors made no further comment (page 452) (*14*).

In the case of flaggers, Elvik and Vaa reported that a 1985 study by Richards et al. found that flaggers reduced average speed by 19% (*14*). Elvik and Vaa considered that this speed reduction "implies a reduction in the expected number of injury accidents of around 40%" (page 452) (*14*). No further details regarding this study are reported by Elvik and Vaa; no AMFs can be derived from these results.

Discussion: Install ITS applications

The CH2M HILL study also investigated the use of ITS applications in work zones. The authors indicate that the complex and individual nature of work zones challenge the application and safety evaluation of specific technologies. Although "there are no studies available that conclusively prove that ITS technologies reduce work zone related crashes, anecdotal information from a variety of work zones on which ITS was used shows that the crash rates were lower than expected" (3168 page 23) (*30*).

Discussion: Implement combinations of traffic control devices

Garber and Woo (1991) developed regression models to examine the effectiveness of various combinations of traffic control devices (from two to six devices such as flaggers, cones, barricades, barriers, static signs, and flashing arrows) in reducing accidents in urban work zones, but the data were insufficient to provide AMFs (*33*). The study was conducted at 26 Virginia sites where construction was taking place for at least 30 days and AADT was at least 3,000 veh/day. The road types modeled were multi-lane urban highways (divided and undivided mixed together) and two-lane urban highways. Project duration ranged from 42 days to 1,096 days. Project length ranged from 0.21 mi to 6.35 mi. The before accident data consisted of accident data for a period just prior to and approximately equal to the duration of the work zone project. The study used accident rates (*33*). Due to the variety of combinations studies and the limited number of sites included, no AMFs can be derived.

In general, flaggers were the most successful and lane-closure barricades were the least successful: "any combination of control devices that includes flaggers will be most effective in reducing accident rates at work zones on urban two-lane highways" (page 267) (*33*). (Flaggers must be properly trained and given adequate breaks.) Lane-closure barricades used in any combination of traffic control devices appeared to result in a slight increase in accidents on multi-lane highways, but not on two-lane highways (*33*).

Garber and Woo recommend the following traffic control device combinations, depending on the road type:

- For two-lane urban highways, the three most effective combinations of traffic control devices were **cones and flaggers**, **barricades and flaggers**, or **static signs and flaggers** (there was no statistically significant difference in the effectiveness of the three combinations). Any combination of traffic control devices including flaggers was found to be more effective than combinations without flaggers.
- For multi-lane urban highways, the most effective combination of traffic control devices was **cones, flashing arrows and flaggers**. Use of barricades as part of any traffic control device combination appears to produce slightly higher accident rates than the same combination of traffic control devices excluding barricades.

AMFs could not be developed based on the Garber and Woo study. No other studies were found that quantified the safety effect of traffic control device combinations.

6.2.2.2. Delineation

Delineation can be used to guide drivers safely along a clear path through work zones. This is especially important where driver expectations are seriously violated, at night, under adverse weather conditions and when drivers may be fatigued.

This section discusses the safety effects of delineation, pavement markings and pavement markers in work zones, specifically temporary pavement markings (overlays). The information currently available is qualitative and tentative.

Exhibit 6-33: Resources examined on the safety effectiveness of delineation in work zones

DOCUMENT	DESCRIPTION	COMMENT
(Kononov, J. and Znamenacek, Z., "Risk Analysis of Freeway Lane Closure During Peak Hour." Washington, D.C., 84th Transportation Research Board Annual Meeting, (2005))	The paper's objective was to create an expert system which would improve the quality of lane closure decisions. The study examined the increased probability of an accident occurring in a work zone.	Not added to synthesis.
(Khattak, A. J., Khattak, A. J., and Council, F. M., "Effects of Work Zone Presence on Injury and Non-Injury Crashes." Accident Analysis and Prevention, Vol. 34, No. 1, Oxford, N.Y., Pergamon Press, (2002) pp. 19-29.)	The authors used regression models to investigate the number of expected crashes by work zone duration (number of days) and work zone length.	Not added to synthesis.
(Bernhardt, K. L., Virkler, M. R., and Shaik, N. M., "Evaluation of Supplementary Traffic Control Measures for Freeway Work-Zone Approaches." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	The study investigated whether three traffic control devices (white lane drop arrows, CB wizard alert system and orange rumble strips) could be used to reduce traffic speed, reduce speed variance and improve advance merging on approaches to freeway work zones.	Not added to synthesis.
(Fontaine, M. D. and Hawkins, G. H., "Catalog of Effective Treatments to Improve Driver and Worker Safety at Short-Term Work Zones." FHWA/TX-01/1879-3, Austin, Texas Department of Transportation, (2001))	The report catalogs devices for improving driver and worker safety at very short-term work zones. Quantitative information is limited to a few speed reduction details.	Not added to synthesis.
(Walker, V. and Upchurch, J., "Effective Countermeasures to Reduce Accidents in Work Zones." FHWA-AZ99-467, Phoenix, Department of Civil and Environmental Engineering, Arizona State University, (1999))	The study reviewed work zone countermeasures and selected six for use in Arizona.	Not added to synthesis.
(Garber, N. J. and Srinivasan, S., "Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds at Work Zones: Phase II." VTRC 98-R10, Charlottesville, Virginia Transportation Research Council, (1998))	The study's investigated the effect of changeable message signs (CMS) with radar on vehicle speeds at three sites.	Not added to synthesis.
(Pal, R. and Sinha, K. C., "Analysis of Crash Rates at Interstate Work Zones in Indiana." Transportation Research Record 1529, Washington, D.C., Transportation Research Board, National Research Council, (1996) pp. 43-53.)	The authors used a before and after study with a comparison group to analyze the relative safety of crossover lane closures (two-way traffic operations) and partial lane closures. Centerline treatment not discussed.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(McCoy, P. T. and Bonneson, J. A., "Work Zone Safety Device Evaluation." SD92-10-F, Pierre, South Dakota Department of Transportation, (1993))	The research evaluated traffic control devices that could improve safety in work zones in South Dakota. The evaluation looked at speed reduction and at driver recognition and comprehension of traffic control.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Stout, D., Graham, J., Bryant-Fields, B., Migletz, J., Fish, J., and Hanscom, F., "Maintenance Work Zone Safety Devices Development and Evaluation." SHRP-H-371, Washington, D.C., Strategic Highway Research Program, National Research Council, (1993))	The study evaluated 25 prototype work zone safety devices designed to protect work crews at short-term (one to 12 hour duration) work zones.	Not added to synthesis.
(Harwood, D. W., "NCHRP Synthesis of Highway Practice Report 191: Use of Rumble Strips to Enhance Safety." Washington, D.C., Transportation Research Board, National Research Council, (1993))	The report provides a synthesis of research into the safety effects of rumble strips.	Not added to synthesis.
(*33*) (Garber, N. J. and Woo, T. H., "Effectiveness of Traffic Control Devices in Reducing Accident Rates at Urban Work Zones." Transportation Quarterly, Vol. 45, No. 2, Washington, D.C., Eno Foundation for Transportation Inc., (1991) pp. 259-270.)	The study used regression models to examine the effectiveness of various combinations of traffic control devices in reducing accidents in urban work zones in Virginia.	Added to synthesis. No AMFs.
(Rouphail, N. M., Mousa, R., Said, K., and Jovanis, P. P., "Freeway Construction Zones in Illinois: A Follow-Up Study. Final Report." FHWA/IL/RC-004, Springfield, Illinois Department of Transportation, (1990))	The study evaluated various traffic control measures used in work zones.	Not added to synthesis.
(*41*) (Dudek, C. L., Huchingson, R. D., Creasey, F. T., and Pendleton, O., "Field Studies of Temporary Pavement Marking at Overlay Project Work Zones on Two-Lane, Two-Way Rural Highways." Transportation Research Record 1160, Washington, D.C., Transportation Research Board, National Research Concil, (1988) pp. 22-34.)	The study analyzed the relative safety of temporary broken line pavement markings (overlays) in highway work zones at seven sites at night.	Added to synthesis. No AMFs.
(27) (Dudek, C. L., Richards, S. H., and Buffington, J. L., "Some Effects of Traffic Control on Four-Lane Divided Highways." Transportation Research Record 1086, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 20-30.)	The study evaluated single lane closures in one direction, and crossover closures with two-lane two-way operations (TLTWO) at nine sites.	Added to synthesis. No AMFs.
(25) (Graham, J. L. and Migletz, J., "Design Considerations for Two-Lane, Two-Way Work Zone Operations." FHWA/RD-83/112, Washington, D.C., Federal Highway Administration, (1983))	The study investigated 22 rural TLTWO sites, which included a variety of crossover designs and centerline treatments. The study calculated accident rates (per MVM) for different centerline treatments.	Added to synthesis. No AMFs
(Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	The study analyzed accidents that occurred before and during construction in 79 zones in seven states in the 1970s. Centerline treatment not discussed.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.

Limited information was found on the safety effectiveness of delineation, pavement markings and pavement markers in work zones. No recent studies were found.

Discussion: Use temporary centerline separation in work zones

Temporary centerline treatments are used to separate traffic where drivers face opposing traffic without a median along two-lane two-way operations (TLTWO) at crossover closures on divided highways. The treatments are intended to prevent accidents that tend to lead to severe injuries and fatalities (such as head-on accidents). Temporary centerline treatments may also be needed on multi-lane undivided highways while a lane is closed for a work zone.

Centerline treatments are not always applied; possibly due to equipment cost, loss of lane width, maintenance costs and related issues, or the need to allow for exceptions for short-term work or the provision of passing opportunities.

The current literature provides limited information. Two important questions that could not be answered by current literature include:

1. Do temporary centerline treatments at work zones impact safety?
2. Are some options (drums, cones, etc.) as effective in preventing head-on accidents as the more expensive options such as portable concrete barriers?

Various temporary centerline treatments are discussed in concert because the studies reviewed did not provide enough information to examine different centerline treatments individually.

The two studies that mentioned centerline separation in work zones were conducted at sites on rural multi-lane highways and freeways. No information was found for urban and suburban arterials. Discussion on centerline separation in work zones was not found for rural two-lane roads in available literature.

Dudek et al. investigated TLTWO and single lane closure designs at work zones and noted the centerline “separation” used at six sites (three of which were single lane closures and three of which were two-lane two-way operations) (*27*). The type of separation was assumed to refer to the centerline treatments at the TLTWO sites, but it is not clear whether the separation on the single lane closure sites was along a centerline or at the lane merge. The types of separation used varied among the six sites included in the Dudek et al. study: cones, pavement markings, portable concrete barriers, and tubular markers. The authors do not explain why a particular centerline treatment was used at a particular site. In addition, the short period of “before” data (one year) limited the analysis. As a result of these difficulties, it is not possible to draw any conclusions regarding the centerline treatments used in the Dudek et al. study.

Graham and Migletz’s 1983 study analyzed accident rates by six centerline treatments at work zones on multi-lane divided highways (*25*). The treatments were:

3. Striping only – double solid yellow centerline (six sites).
4. Raised pavement markers and striping – double solid yellow centerline with single yellow bi-directional raised pavement markers at 50 ft intervals (one site).
5. Cones and striping - double solid yellow centerline with traffic cones at 200 ft intervals (six sites).
6. Raised pavement markers and cones – pairs of yellow bi-directional raised pavement markers at 10 ft intervals with traffic cones at 200 ft intervals (one site).
7. Tubular markers and striping – double solid yellow centerline with 2 ft tall plastic tubular markers at 200 ft intervals (two sites).
8. Portable concrete barrier – portable concrete barrier (PCB) with 3 in circular yellow delineators on top at 20 ft intervals (one site).

The authors do not explain why a particular treatment was used at a particular site and their discussion of centerline treatments was presented only in qualitative terms. In short, Graham and Migletz concluded that (*25*):

- It may be desirable to combine striping (double solid yellow centerlines) with other centerline treatments because work zones with only double yellow centerlines had the highest accident rates and the vehicle encroachment rate into opposing lanes was much higher than for any other type of centerline studied; and
- Portable concrete barriers are expensive, but may be justified at sites such as some bridge projects where the work zone length is short, traffic volume is high (10,000 or more veh/day) and approach speed is high. However, portable concrete barriers do not compensate for poor geometric design.

There was insufficient information in the Graham and Migletz paper to determine AMFs.

Discussion: Use temporary pavement markings (overlays)

In 1991, Garber and Woo modeled six traffic control devices including temporary pavement markings (*33*). One of the six traffic control devices was temporary pavement markings, and the findings concluded that markings did not feature in the most effective combinations of traffic control devices for two-lane highways.

In 1988, Dudek et al. investigated the relative safety of 1 ft, 2 ft, and 4 ft long temporary broken centerline line pavement markings (overlays) at seven work zones at night (*41*) The work zones sites were on two-lane two-way rural highways with 12 ft lanes and paved shoulders and volumes from 2,500 to 6,700 veh/day. The test conditions were carefully controlled to include dry weather conditions, sites with both curves and tangents, centerline stripes only (no edgelines), and the use of a 40 ft pavement marking cycle. The 1 ft, 2 ft, and 4 ft long broken line markings were evaluated in terms of vehicle speeds, lateral distance from the centerline, lane straddling and erratic maneuvers. The researchers also analyzed driver opinions (four drivers per site) of the broken line markings. Accident experience was not studied.

Dudek et al. concluded that all three striping patterns provided adequate delineation on rural two-lane two-way highways, but noted that the findings cannot be generalized to situations not tested (*41*). The study was criticized by a reviewer (published in the report) for using near perfect conditions for assessing retro-reflectivity (for example, roadways that were dry, very dark and had limited curvature) and for the absence of edgelines, which may have focused drivers' attention on the centerlines. There was concern that the study could have negative consequences by not establishing a need for stronger pavement markings. Nevertheless, the authors concluded that "The data failed to indicate major differences"(page 33) between the length and spacing of the temporary stripes" (*41*). The controversy created by the study indicates a clear need for additional research.

No AMFs could be determined from the available literature.

6.2.2.3. Rumble Strips

Rumble strips warn drivers by creating vibration and noise when driven over. The objective of rumble strips is to reduce crashes caused by drowsy or inattentive drivers. In general, rumble strips are used in areas where the noise generated is unlikely to disturb adjacent residents; that is, in non-residential areas.

Temporary rumble strips may be used in work zones as a traffic control device.

Exhibit 6-34: Resources examined on the safety effectiveness of rumble strips in work zones

DOCUMENT	DESCRIPTION	COMMENT
(Kononov, J. and Znamenacek, Z., "Risk Analysis of Freeway Lane Closure During Peak Hour." Washington, D.C., 84th Transportation Research Board Annual Meeting, (2005))	The paper's objective was to create an expert system which would improve the quality of lane closure decisions. The study examined the increased probability of an accident occurring in a work zone.	Not added to synthesis.
(Khattak, A. J., Khattak, A. J., and Council, F. M., "Effects of Work Zone Presence on Injury and Non-Injury Crashes." Accident Analysis and Prevention, Vol. 34, No. 1, Oxford, N.Y., Pergamon Press, (2002) pp. 19-29.)	The authors used regression models to investigate the number of expected crashes by work zone duration (number of days) and work zone length.	Not added to synthesis.
(Bernhardt, K. L., Virkler, M. R., and Shaik, N. M., "Evaluation of Supplementary Traffic Control Measures for Freeway Work-Zone Approaches." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	The study investigated whether three traffic control devices (white lane drop arrows, CB wizard alert system and orange rumble strips) could be used to reduce traffic speed, reduce speed variance and improve advance merging on approaches to freeway work zones.	Not added to synthesis.
(Fontaine, M. D. and Hawkins, G. H., "Catalog of Effective Treatments to Improve Driver and Worker Safety at Short-Term Work Zones." FHWA/TX-01/1879-3, Austin, Texas Department of Transportation, (2001))	The report catalogs devices for improving driver and worker safety at very short-term work zones. Quantitative information is limited to a few speed reduction details.	Not added to synthesis.
(Walker, V. and Upchurch, J., "Effective Countermeasures to Reduce Accidents in Work Zones." FHWA-AZ99-467, Phoenix, Department of Civil and Environmental Engineering, Arizona State University, (1999))	The study reviewed work zone countermeasures and selected six for use in Arizona.	Not added to synthesis.
(Garber, N. J. and Srinivasan, S., "Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds at Work Zones: Phase II." VTRC 98-R10, Charlottesville, Virginia Transportation Research Council, (1998))	The study's investigated the effect of changeable message signs (CMS) with radar on vehicle speeds at three sites.	Not added to synthesis.
(Pal, R. and Sinha, K. C., "Analysis of Crash Rates at Interstate Work Zones in Indiana." Transportation Research Record 1529, Washington, D.C., Transportation Research Board, National Research Council, (1996) pp. 43-53.)	The authors used a before and after study with a comparison group to analyze the relative safety of crossover lane closures (two-way traffic operations) and partial lane closures. Centerline treatment not discussed.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.
(McCoy, P. T. and Bonneson, J. A., "Work Zone Safety Device Evaluation." SD92-10-F, Pierre, South Dakota Department of Transportation, (1993))	The research evaluated traffic control devices that could improve safety in work zones in South Dakota. The evaluation looked at speed reduction and at driver recognition and comprehension of traffic control.	Not added to synthesis.
(Stout, D., Graham, J., Bryant-Fields, B., Migletz, J., Fish, J., and Hanscom, F., "Maintenance Work Zone Safety Devices Development and Evaluation." SHRP-H-371, Washington, D.C., Strategic Highway Research Program, National Research Council, (1993))	The study evaluated 25 prototype work zone safety devices designed to protect work crews at short-term (one to 12 hour duration) work zones.	Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(Harwood, D. W., "NCHRP Synthesis of Highway Practice Report 191: Use of Rumble Strips to Enhance Safety." Washington, D.C., Transportation Research Board, National Research Council, (1993))	The report provides a synthesis of research into the safety effects of rumble strips.	Not added to synthesis.
(*32*) (McCoy, P. T. and Bonneson, J. A., "Work Zone Safety Device Evaluation." *SD92-10-F*, Pierre, South Dakota Department of Transportation, (1993))	The research evaluated traffic control devices that could improve safety in work zones in South Dakota. The evaluation looked at speed reduction and at driver recognition and comprehension of traffic control.	Limited qualitative information. Added to synthesis. No AMFs.
(*33*) (Garber, N. J. and Woo, T. H., "Effectiveness of Traffic Control Devices in Reducing Accident Rates at Urban Work Zones." Transportation Quarterly, Vol. 45, No. 2, Washington, D.C., Eno Foundation for Transportation Inc., (1991) pp. 259-270.)	The study used regression models to examine the effectiveness of various combinations of traffic control devices in reducing accidents in urban work zones in Virginia.	Added to synthesis. No AMFs.
(Rouphail, N. M., Mousa, R., Said, K., and Jovanis, P. P., "Freeway Construction Zones in Illinois: A Follow-Up Study. Final Report." FHWA/IL/RC-004, Springfield, Illinois Department of Transportation, (1990))	The study evaluated various traffic control measures used in work zones.	Not added to synthesis.
(Dudek, C. L., Huchingson, R. D., Creasey, F. T., and Pendleton, O., "Field Studies of Temporary Pavement Marking at Overlay Project Work Zones on Two-Lane, Two-Way Rural Highways." Transportation Research Record 1160, Washington, D.C., Transportation Research Board, National Research Concil, (1988) pp. 22-34.)	The study analyzed the relative safety of temporary broken line pavement markings (overlays) in highway work zones at seven sites at night.	Not added to synthesis. No AMFs.
(Dudek, C. L., Richards, S. H., and Buffington, J. L., "Some Effects of Traffic Control on Four-Lane Divided Highways." Transportation Research Record 1086, Washington, D.C., Transportation Research Board, National Research Council, (1986) pp. 20-30.)	The study evaluated single lane closures in one direction, and crossover closures with two-lane two-way operations (TLTWO) at nine sites.	Not added to synthesis. No AMFs.
(Graham, J. L. and Migletz, J., "Design Considerations for Two-Lane, Two-Way Work Zone Operations." FHWA/RD-83/112, Washington, D.C., Federal Highway Administration, (1983))	The study investigated 22 rural TLTWO sites, which included a variety of crossover designs and centerline treatments. The study calculated accident rates (per MVM) for different centerline treatments.	Not added to synthesis. No AMFs
(Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	The study analyzed accidents that occurred before and during construction in 79 zones in seven states in the 1970s. Centerline treatment not discussed.	Reference suggested by NCHRP 17-18(4). Not added to synthesis.

Discussion: Install portable transverse rumble strips as additional warning in advance of a STOP sign on a work zone segment

Walker and Upchurch cited a 1996 study (by Gent and Gerken) in which portable transverse rumble strips were found to be the most effective device rated for getting the attention of motorists at work zones, but the strips tended to buckle and move as vehicles passed over them (*34*). Walker and Upchurch did not report the road type, volume, and other site characteristics.

McCoy and Bonneson evaluated portable rumble strips intended to improve driver recognition of the STOP sign on the approach to a work zone at a bridge (*32*). The study site was a two-lane road with ADT of 830 veh/day. The portable rumble strips were not effective in improving driver compliance with the STOP sign. Lack of activity at the work zone while the study took place may have confounded the results. No AMFs can be derived from this study.

6.2.2.4. Speed Limits and Speed Zones

Many traffic control devices used in work zones aim to reduce speed of the traffic. Walker and Upchurch point out that "it has been widely accepted that the primary cause for increased accidents in construction work zones is the result of vehicles traveling at excessive speeds" (page 29) (*34*). The speed of vehicles traveling through a work zone can be used as a surrogate for the safety of the work zone, if the relationship is established. Reduced speed limits may lead to lower speeds and to fewer and/or less severe accidents (*34*).

The conventional practice for regulating speeds in work zones follows the static signing procedures using regulatory or advisory speed signs found in the Manual on Uniform Traffic Devices (MUTCD) (*3*). The approach adopted to reduce vehicle speeds depends on the road type and setting, the work zone layout, the work zone duration, whether the work zone is static or moving, the cost of the speed control, and institutional constraints (such as the availability of a police presence and the availability of trained flaggers). Combinations of speed controls are commonly used.

Traffic control devices used to reduce speed include passive speed control, such as static signs intended to alert drivers to conditions or speed reductions ahead, and channelization devices used to direct traffic through or around hazards. Passive speed control may be sufficient where drivers have enough time and information to make reasonably safe speed decisions without the need for additional prompting or reinforcement.

Active speed control may be used where drivers do not drive at safe and appropriate speeds. Active speed controls display personalized real-time information or enforce compliance with the passive measures. Examples include changeable message signs, flaggers, lane width reductions, transverse rumble strips and law enforcement.

Posted speed limits and speed variance are particularly important at work zones. Motorists need a common set of rules that encourage predictable and uniform driving behavior and the safe flow of traffic.

Temporary speed limits must be set with care. Garber and Srinivasan point out that speed reduction can lead to congestion and rear-end accidents (which are particularly common at work zones) (*35*). Weiss and Schifer note that speed limits should not be dramatically reduced because the decision to adopt a "substantially different speed can contradict the perception of the safe driving speed for the majority of drivers and thus can produce disturbances in the driving stream" (page 5) (*36*).

There are no uniform guidelines and suitable engineering studies for determining appropriate guidelines for speed limits in work zones. "There are inconsistencies in the methods used to determine work zone speed limits, noncompliance with the posted speed limit by motorists, and a growing practice of establishing work zone speed limits through administrative decision without the benefit of an engineering study" (page 29) (*34*). Passive, nonspecific measures such as signs are thought to be less effective than active measures such as flaggers and changeable message signs, but how much less effective is unknown (*35*). Rigorous study designs are hard to achieve. Driver behavior in a work zone is influenced by the geometry of the roadway, the signage, the type of construction, vehicle mix, etc., making complete isolation of individual factors difficult.

This section provides information on the effectiveness of traffic control devices and operational elements that affect the operating speed of vehicles approaching work zones and passing through work zones. Limited information was found, and is discussed here, on temporary speed limits, speed zoning, flaggers, the use of innovative flagging procedures, changeable/variable message signs (CMS), speed display trailers, changeable message signs with radar/personalized messages, variable speed limit (VSL) systems, radar drones (unmanned radar), radar activated horns, cones combined with (unspecified) warnings, lane width reduction, transverse rumble strips applied to reduce speeds prior to or in work zones, white lane drop arrows, transverse rumble strips combined with CB messages, Citizens Band (CB) messages, and law enforcement.

Exhibit 6-35: Resources examined on the relationship of speed control and safety in work zones

DOCUMENT	DESCRIPTION	COMMENT
(*14*) (Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	Limited qualitative information. Added to synthesis.
(*37*) (Bernhardt, K. L., Virkler, M. R., and Shaik, N. M., "Evaluation of Supplementary Traffic Control Measures for Freeway Work-Zone Approaches." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	The study investigated whether three traffic control devices (white lane drop arrows, CB wizard alert system and orange rumble strips) could be used to reduce traffic speed, reduce speed variance and improve advance merging on approaches to freeway work zones.	Reference suggested by NCHRP 17-18(4). Limited qualitative information. Added to synthesis. No AMFs.
(*38*) (Fontaine, M. D. and Hawkins, G. H., "Catalog of Effective Treatments to Improve Driver and Worker Safety at Short-Term Work Zones." FHWA/TX-01/1879-3, Austin, Texas Department of Transportation, (2001))	The report catalogs devices for improving driver and worker safety at very short-term work zones. Quantitative information is limited to a few speed reduction details.	Limited quantitative information. Added to synthesis. No AMFs.
(*36*) (Weiss, A. and Schifer, J. L., "Assessment of Variable Speed Limit Implementation Issues." NCHRP 3-59, Washington, D.C., Transportation Research Board, National Research Council, (2001))	The study is a detailed assessment of the effectiveness of variable speed limits (VSL). Expected completion date is July 2005.	Limited qualitative information. Added to synthesis. No AMFs.
(*34*) (Walker, V. and Upchurch, J., "Effective Countermeasures to Reduce Accidents in Work Zones." FHWA-AZ99-467, Phoenix, Department of Civil and Environmental Engineering, Arizona State University, (1999))	The study reviewed work zone countermeasures and selected six for use in Arizona.	Limited quantitative information. Added to synthesis. No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
(*35*) (Garber, N. J. and Srinivasan, S., "Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds at Work Zones: Phase II." VTRC 98-R10, Charlottesville, Virginia Transportation Research Council, (1998))	The study investigated the effect of changeable message signs (CMS) with radar on vehicle speeds at three sites.	Reference suggested by NCHRP 17-18(4). Very limited quantitative information. Added to synthesis. No AMFs.
(*39*) (Freedman, M., Teed, N., and Migletz, J., "Effect of Radar Drone Operation on Speeds at High Crash Risk Locations." Transportation Research Record 1464, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 69-80.)	The study compared vehicle speeds at work zones and high crash locations with and without radar drones at 12 sites.	Reference suggested by NCHRP 17-18(4). Qualitative information. Added to synthesis. No AMFs.
(*32*) (McCoy, P. T. and Bonneson, J. A., "Work Zone Safety Device Evaluation." SD92-10-F, Pierre, South Dakota Department of Transportation, (1993))	The research evaluated traffic control devices that could improve safety in work zones in South Dakota. The evaluation looked at speed reduction and at driver recognition and comprehension of traffic control.	Reference suggested by NCHRP 17-18(4). Limited qualitative information. Added to synthesis. No AMFs.
(*40*) (Richards, S. H., Wunderlich, R. C., Dudek, C. L., and Brackett, R. Q., "Improvements and New Concepts for Traffic Control in Work Zones. Volume 4. Speed Control in Work Zones." FHWA/RD-85/037, College Station, Texas A&M University, (1985))	Evaluated four work zone speed reduction measures; studies conducted on an undivided multilane urban arterial, an urban freeway, and two rural freeways; reports results from 2-lane rural highway also	Reference suggested by NCHRP 17-18(4). Added to synthesis. No AMFs.
(*24*) (Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident and Speed Studies in Construction Zones." FHWA-RD-77-80, Washington, D.C., Federal Highway Administration, (1977))	Part 2 of the study was a field test that investigated speed reduction methods at three work zones. The study used traffic conflicts.	Reference suggested by NCHRP 17-18(4). Qualitative information. Added to synthesis. No AMFs.

Numerous studies have investigated speed reduction in work zones, but there is very little detailed or quantitative information available about establishing effective speed limits or the safety effects of speed reductions. For example, the safety effects of temporary speed limit signs and speed zoning are unknown. Whether temporary speed limit signs should be advisory or regulatory, from their safety effectiveness aspect is also unknown.

Limited information was found for temporary speed limits, flaggers, changeable / variable message signs (CMS), variable speed limit (VSL) systems, radar, rumble strips, white lane drop arrows and Citizens Band (CB) messages, and most of the information was qualitative.

Discussion: Install temporary speed limit signs and speed zoning

Walker and Upchurch (1999) noted in their literature review that most studies had found that both advisory and regulatory temporary speed limit signs “have shown either only small effects or no effect of work zone speed limits on vehicle speeds” (page 29) and “work zone speed limits by themselves are relatively ineffective in influencing traffic speeds” (page 31) ((*34*)).

Graham et al. (1977) investigated speed reduction methods at three sites: an urban four-lane undivided arterial, an urban four-lane divided freeway, and a rural interstate highway. They concluded that "construction zones with reduced speed limits do not experience lower accident rates than other zones" (page 83) and that "Drivers adjust speed and position based on the environment (geometrics of zone, lateral clearance and devices) more than on signing" (page 84) (*24*). They also concluded that speed zoning "does not reduce mean vehicle speed and does increase conflicts in the transition area" (page 83) (*24*). The study did not provide AMFs for speed limits signs.

Discussion: Use flaggers

Flaggers may be used to control traffic and reduce traffic speed through work zones. Elvik and Vaa's overview of road safety mention only one study that considered flaggers (*14*). They reviewed a 1985 study by Richards et al. (*40*) where flaggers were found to reduce average speed by 19% on rural two-lane roads, rural freeways, urban freeways, and undivided urban arterials. Elvik and Vaa considered that this speed reduction "implies a reduction in the expected number of injury accidents of around 40%" (page 452) (*14*). Volumes were not stated. No AMFs can be determined.

Discussion: Use innovative flagging procedures

Walker and Upchurch's review of work zone countermeasures included flashing stop/slow paddles (*34*). The paddles featured high intensity lights that the flagger could turn on if a motorist appeared to be ignoring the flagger. Walker and Upchurch cited studies (no reference details given, page 55) that found that drivers rated the flashing stop/slow paddles as effective, especially at night. There were no AMFs. The flaggers reported that they felt better protected. The road type for this study was not stated, but the tests were conducted on urban and rural roads in several states.

McCoy and Bonneson evaluated two innovative flagging procedures in advance of a single lane closure on a freeway compared to no flaggers prior to the work zone (*32*). The objective of the flagging procedures was to reduce traffic speeds. Instead of holding a STOP/SLOW sign paddle, the flagger held a 45 mph sign paddle in one hand and used the other hand to motion the traffic to slow down. The other procedure was similar, but included a larger sign paddle and bright coveralls.

McCoy and Bonneson comment, "The innovative flagging procedures were effective in reducing the speed of traffic approaching the work zone. The average traffic speeds were lower after the flagging procedures were instituted" (page 49) (*32*). "The first procedure resulted in speed reductions of 15.2 and 11.1 mph at the beginning and end of the taper respectively" (page 49), and the second procedure "resulted in speed reductions of 12.4 and 9.2 mph at the beginning and end of the taper respectively" (page 49) (*32*). The results were not compared with speed reductions for standard flagging procedures. Difficulties with the procedures included flagger fatigue and boredom, and ensuring that flaggers followed the procedures consistently. No AMFs can be determined from this study.

A 1985 study by Richards et al. was conducted at six sites on rural two-lane roads, rural freeways, urban freeways, and undivided urban arterials (*40*). The study compared MUTCD flaggers with innovative flagging on one side of the road and on both sides of the road.

Richards et al. noted that the best flagging treatment was an innovative procedure that involved the flagger motioning traffic to slow down with one hand and then pointing to the nearby speed sign (page x) (*40*). This procedure "resulted in larger average speed reductions than MUTCD flagging at five of the six study sites, but the differences were small" (2 to 4 mph) (page xi) (*40*). Speed reductions were greater on rural two-lane roads and urban arterials than on urban or rural freeway sites. "The results also indicated that flagging effectiveness may be improved on freeways by having a flagger on both sides of the travel lanes" (page xi) (*40*). No AMFs can be determined.

Discussion: Install changeable message signs (CMS)

Walker and Upchurch summarized two studies that evaluated changeable (or variable) message signs (CMS) (*34*). The first study, a 1992 New York study by Migletz et al., found that CMS reduced speeds, but the speeds remained 10 mph above the work zone speed limit and there were concerns that increased variance in the vehicle speeds might increase safety problems. Walker and Upchurch do not report operating speeds for this study prior to the implementation of CMS. The second study, a 1992 Illinois study by Benekohal, investigated CMS under three sets of circumstances: one CMS outside the work zone; one CMS within the work zone; and two CMSs within the work zone. All the signs used the same alternating message, “WORKERS AHEAD” and “SPEED LIMIT 45 MPH”. The study found that “the CMS only affected the speeds of vehicles close to the CMS” (page 48) (*34*). The road type for the two studies cited was not stated. No AMFs can be determined.

Garber and Srinivasan mention that Richards et al. found that CMS are more effective when used in combination with other treatments, such as static signs or flaggers (*35*). The road type for the study cited was not stated. No further details are noted.

Richards et al.’s 1985 study was conducted at six sites on rural two-lane roads, rural freeways, urban freeways, and undivided urban arterials (*40*). This study found a 7% speed reduction for CMS on rural freeways, urban freeways, and undivided urban arterials (CMS were not tested on rural two-lane roads).

No AMFs can be determined, but Elvik and Vaa reported that a speed reduction of 7% “implies a reduction in the expected number of injury accidents of around 15%” (page 452) (*14*).

Discussion: Install changeable message signs with radar and personalized messages (including speed display trailers)

Changeable (or variable) message signs (CMS) equipped with a radar unit are an alternative to the high costs involved in having law enforcement officers stationed at work zones. CMS with radar supply reliable and up-to-date warning messages to speeding drivers.

Garber and Srinivasan noted that a 1986 study of CMS with radar by Richards and Dudek found that CMS with automated speed and message display (ASMD) seemed to reduce speeds (*35*). The road type for the study cited was not stated, and quantification of the speed reduction was not reported.

Rural two-lane roads

Fontaine and Hawkins included portable variable message signs (changeable message signs) and speed display trailers in their catalog of devices found to be effective for improving driver and worker safety at rural, short-term (typically a single day) work zones where safety treatments must be set up easily and quickly (*38*). The road type was not specified, but the photos in the report appear to be of rural two-lane roads. All the devices were evaluated in terms of their impact on traffic speeds, conflicts, etc. AMFs could not be derived due to insufficient quantitative information. Exhibit 6-36 shows how changeable message signs and speed display trailers reduced vehicle speeds and the percentage of drivers who were speeding both before the taper and in the work zone. AMFs cannot be derived from these results.

Exhibit 6-36: Effect of portable variable message signs and speed display trailers on speed and the percentage of drivers who were speeding (38)

	Speed		% Speeding	
Treatment	**Before taper**	**Work zone**	**Before taper**	**Work zone**
Changeable message signs	-0.5 mph	-1.0 mph	No change	-3.0%
Speed display trailer	-5.0 mph	-3.5 mph	-13.0%	-6.0%

Rural multi-lane highways

Garber and Srinivasan cite a 1994 Garber and Patel study that found that personalized messages aimed at high speed drivers appeared to be useful and that CMS with radar were "more effective than static MUTCD signs in altering drivers' behavior in work zones" (page 2) (*35*). The study was conducted on interstate highways.

Garber and Srinivasan examined the effect of the duration of exposure to CMS with radar in work zones. They also examined the effectiveness of CMS with radar in reducing speeds and influencing speed profiles. The study was conducted on two interstates and one primary route. The researchers noted high-speed drivers who triggered the CMS and checked them at the beginning, middle and end of the work zone. The study found that CMS with radar reduced speeds by 8 to 10 mph at work zones, and that speeds were reduced for all vehicle types (*35*).

Garber and Srinivasan also indicate that CMS were effective in controlling vehicle speeds even at work zone projects of long duration (e.g., more than seven days and up to seven weeks). A second CMS might be useful in long work zones (e.g., longer than 1.06 km or 3,500 ft) to reduce the tendency for vehicles to speed up as they approach the end of the work zone. "CMS with radar is indeed a very effective device for controlling speeds and speed variances in short-term and long-term work zones" (page 59) (*35*).

CMS with radar appear to reduce operational speeds through work zones on rural multi-lane highways. No measure of the accident experience was noted in the literature reviewed; therefore AMFs could not be developed.

Freeways; Expressways

Walker and Upchurch cited a 1995 British study by Symonds Travers Morgan Ltd (*34*). The British study investigated CMS that displayed the license plate and speed of a speeding vehicle to drivers on a rural divided freeway. Before and after speed studies showed that the immediate feedback given to drivers led to impressive and long lasting results in reducing driver speed (page 52) (*34*). The number of PDO and injury accidents dropped. The index of effectiveness for PDO accidents was 0.52 (s = 0.39). The index of effectiveness for injury accidents was 0.25 (s = 0.81). The s ideal was calculated using the daily average number of PDO or injury accidents in the before and "during" periods (PDO: 0.26 and 0.29; Injury: 0.03 and 0.01, respectively) and the ratio of before/"during" duration (299 days and 142 days respectively) to reach an estimate of the standard error. In both cases, an MCF of 3.0 was applied to s ideal because the British study was a cited work. The volumes and other characteristics of the study are unknown.

McCoy and Bonneson investigated speed monitoring displays in advance of a single lane closure work zone on a freeway (*32*). The "speed monitoring displays were effective in reducing the speed of traffic approaching the work zone" (page 38). Speed reductions averaged only 0.6 mph at 4,000 ft in advance of the taper. The reductions were 4 mph at the beginning of the taper and 4 mph at the end of the taper. The volumes and other characteristics of the study are unknown. No accident experience was reported; therefore no AMFs could be developed.

Urban and suburban arterials

No studies found.

Discussion: Install Variable Speed Limit (VSL) systems

As defined by the FHWA, variable speed limits systems provide real-time information on the appropriate operating speed for current road conditions based on traffic volumes, traffic speed, weather, and other elements.

Weiss and Schifer found that work zones are suited to experimental and ongoing variable speed limit (VSL) applications, which are designed to reduce the speed variations that lead to reduced safety (*36*). The interim report for this project states that real time portable VSL systems may reduce rear-end accidents by reducing congestion and controlling lane merging at work zones. This study is on-going, and is expected to conclude in July 2005.

Treatment: Install radar drones (unmanned radar)

Rural two-lane roads

Fontaine and Hawkins investigated radar drones (unmanned radar) at rural, short-term (typically a single day) work zones where safety treatments must be set up easily and quickly. The road type was not specified, but the photos appear to be of rural two-lane roads.

Exhibit 6-37 shows Fontaine and Hawkins's findings regarding how radar drones reduced vehicle speeds and the percentage of drivers who were speeding before the taper and in the work zone (*38*). The effects on speed were minimal. AMFs cannot be developed from this study.

Exhibit 6-37: Effect of radar drones (unmanned radar) on speed and the percentage of drivers who were speeding (38)

Treatment	Speeds		% Speeding	
	Before taper	**Work zone**	**Before taper**	**Work zone**
Radar drone	-2.0 mph	-1.0 mph	-1.0%	+0.5%

Walker and Upchurch cited a 1992 study by Benekohal that found that where radar drones were used, drivers of vehicles equipped with radar detection devices reduced speed, but the drivers soon realized that no police were present (*34*).

Rural multi-lane highways

Freedman et al.'s 1994 study investigated the use of radar drones to reduce speeds in work zones (*39*). The study compared vehicle speeds with and without radar drones at 12 sites in Missouri. The 12 sites included six long- and short-term work zones sites on urban and rural interstates and on urban and rural roadways. Volumes at the 12 sites ranged from 20,000 veh/day to 70,000 veh/day.

Freedman et al. found that mean speeds at the 12 sites were "moderately lower when radar was operating" (page 69) and speed reductions at work zones were "moderate at most": 3.4 mph (5.5 km/h) (page 78) (*39*).

There were "more meaningful reductions in the number of vehicles exceeding the speed limit by more than 10 mph" (page 69) (*39*). Speeds remained well above the speed limit even when the radar was operating. The researchers concluded that "the operation of drone radar can somewhat reduce the speeds of passenger vehicles and tractor-trailer combinations at many long- and short-term construction and maintenance zones" (page 78) (*39*). Freedman et al. note that the effects on speed were also felt for up to 0.8 mi (1.3km) downstream of the work zones. No AMFs could be derived.

Freeways; Expressways; Urban and suburban arterials

No studies found.

Discussion: Install radar activated horn system

A 1992 study by Benekohal, cited by Walker and Upchurch, investigated a radar activated horn system (*34*). Vehicles traveling over a certain speed triggered the horn to produce an audible reminder that could be heard for a minimum of one mile and a maximum of three miles. The horn system "appeared to have some speed reduction effect on the motorists" (page 49), but further research was recommended into the most suitable detection distance, the human factors involved, and the noise problem created by the horn. The road type for the study cited was not stated.

Discussion: Use cones combined with warnings about the presence of work zones

Elvik and Vaa reported that a 1985 Richards et al. study found that cones combined with warnings about the presence of work zones led to an average reduction in speed of 7% (*14*). Elvik and Vaa considered that this speed reduction "implies a reduction in the expected number of injury accidents of around 15%" (page 452) (*14*). The setting and the type of warning are not reported by Elvik and Vaa.

Discussion: Reduce lane width

Richards et al.'s 1985 study was conducted at six sites on rural two-lane roads, rural freeways, urban freeways, and undivided urban arterials (*40*). This study found a 7% speed reduction when lane width was reduced.

No AMFs can be determined, but Elvik and Vaa reported that a speed reduction of 7% "implies a reduction in the expected number of injury accidents of around 15%" (page 452) (*14*).

Discussion: Install transverse rumble strips in advance of work zone

McCoy and Bonneson's 1993 study investigated portable transverse rumble strips used in advance of a single lane closure work zone on a rural two-lane highway in South Dakota (*32*). The volume at the site was 830 veh/day. The researchers concluded that portable transverse rumble strips did not reduce vehicle speeds. Speeds were higher with the rumble strips than without them. As the location used for testing may not have been suitable, the findings were considered uncertain; no AMFs could be developed.

Bernhardt et al.'s 2001 study investigated whether removable orange raised rumble strips with CB (Citizens Band) messages could be used to reduce traffic speed, reduce speed variance and improve advance merging on approaches to freeway work zones. The study took place at a long-term work zone on a rural interstate highway (14,600 veh/day) in Missouri (*37*).

The rumble strips were evaluated while the CB messages were operating. Bernhardt et al. found that "rumble strips can be expected to promote …. some decreases in mean speeds of vehicles approaching an interstate highway work zone with a lane drop" (page 1) (*37*). They also found that the use of rumble strips in conjunction with CB messages improved mean speed characteristics (the study reviewed mean speed, speed variance, 85^{th} percentile speed, fastest 15% of vehicles, percentage of vehicles below the speed limit, and 10-mph pace). No accident information is found; no AMFs could be developed.

Discussion: Use white lane drop arrows

The 2001 Bernhardt et al. study found that removable "white lane drop arrows can be expected to promote …. some decreases in mean speeds of vehicles approaching an interstate highway work zone with a lane drop" (page 1) (*37*). The arrows were associated with a decrease in speed near the work zone, but speed increased upstream from the work zone. No accident experience is reported; no AMFs could be developed.

Discussion: Broadcast Citizens' Band (CB) messages

Bernhardt et al.'s 2001 study found that "CB messages can be expected to promote …. some decreases in mean speeds of vehicles" (page 1) at a work zone (*37*). Like white lane drop arrows, CB messages were associated with a decrease in speed near the work zone and an increase in speed upstream from the work zone (page 18) (*37*). No accident experience is reported; no AMFs could be developed.

Discussion: Police enforcement of speeds

Richards et al.'s study (1985) was conducted at six work zone sites on rural two-lane roads, rural freeways, urban freeways, and undivided urban arterials (*40*). Richards et al. investigated speed reduction using a police traffic controller (speed reductions of 9 to 13 mph), and a stationary patrol car (4 to 12 mph). They also investigated a stationary patrol car with emergency lights or radar. This performed "slightly better" (page xi) than the stationary patrol car. The fourth type of law enforcement was a circulating patrol car which was used only on the rural two-lane sites and which was the least effective (2 to 3 mph.) (*40*).

No AMFs can be determined from the Richards et al. study (*40*), but the average speed reduction for the law enforcement approaches was 18% which suggests a substantial accident reduction given that Elvik and Vaa considered that a speed reduction of 19% for flagging "implies a reduction in the expected number of injury accidents of around 40%" (page 452) (*14*).

Graham et al. (1977) investigated speed reduction methods at three sites: an urban four-lane undivided arterial, an urban four-lane divided freeway, and a rural interstate highway, and found that "Enforcement patrols … decrease vehicle speeds near where they are installed, but their speed reduction effect is only effective over a short length of highway" (page 84) (*24*). No accident experience is reported; no AMFs could be developed.

Summary

The safety effects of the various treatments for reducing speed in work zones cannot be quantified at this time, but the literature currently available suggests that the most effective treatments for reducing speeds through work zones are:

- Changeable message signs with radar and personalized messages,
- Flaggers using innovative flagging procedures, and
- Flaggers using standard flagging procedures.

The speed reductions achieved by these treatments imply injury accident reductions in the region of 40% (*14*).

The following treatments discussed in the current literature achieved speed reductions that imply injury accident reductions in the region of 15% (*14*):

- Changeable message signs,
- Cones combined with (unspecified) warnings, and
- Lane width reduction.

The following treatments discussed in the current literature produced inconclusive results or had limited success in reducing work zone speeds:

- Radar drones (unmanned radar);
- Portable variable message signs;
- Speed display trailers;
- Advisory and regulatory temporary speed limit signs;
- Reduced speed limits in work zones, speed zoning;
- White lane drop arrows;
- Transverse rumble strips combined with CB messages; and
- CB messages.

Further research is necessary for all treatments, all road types, and all crash types. In the case of changeable message signs in work zones, the results vary depending on whether radar and personalized messages were added and on other circumstances at the site. The effects ranged from large to small, raising many questions and suggesting that the results available at present may be subject to change.

6.2.3. Pedestrian and Bicyclist Safety at Work Zones [Future Edition]

The accommodation of these road users is of particular importance for long duration work zones on urban and suburban arterials. In future editions of the HSM, the safety effect of various work zone design and traffic control elements may be discussed here. Potential resources are listed in Exhibit 6-38.

Exhibit 6-38: Potential resources on the safety considerations for pedestrians and bicyclists in work zones.

DOCUMENT
(Lalani, N., "Alternative Treatments for At-Grade Pedestrian Crossings." Washington, D.C., Institute of Transportation Engineers, (2001))
(Staplin, L., Lococo, K., Byington, S., and Harkey, D., "Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians." FHWA-RD-01-051, Washington, D.C., Federal Highway Administration, (2001))

6.2.4. Safety Effects of Other Work Zone Elements

Other work zone elements that may have a safety impact include illumination and weather. These elements are discussed in the following sections.

6.2.4.1. Illumination

Illumination of work zones is a critical element in particular if the zone is active during the night.

The treatment discussed in this section is the effect on safety of providing artificial lighting for the duration of a highway work zone. This refers to the use of artificial lighting in work zones for the duration of the work.

No study has been found that has evaluated the effect on safety of illumination in highway work zones. Since there are no studies, effects could be estimated by relying on studies that have evaluated the effects of roadway lighting in general, i.e., not specifically in work zones. However, due to the special operations that can occur in work zones, this may not provide the most conservative AMFs.

Evidence regarding the effect of illumination is taken from a meta-analysis (Elvik 1995) of 37 evaluation studies containing 142 estimates of effect. This analysis has subsequently been updated by the addition of new studies, increasing the number of studies to 40 and the number of estimates of effect to 152.

Studies have been classified in three groups according to study quality. Studies rated as high quality include studies using both an internal and external comparison group (the distinction between external and internal comparison is explained below) and matched case-control studies. Studies rated as medium quality include studies that provide data on traffic volume in addition to accident data, and studies using an external comparison group only. Studies rated as low quality include studies that use only an internal comparison group and simple (as opposed to matched) case-control studies. Most studies, representing 74% of the estimates of effect, have been rated as low quality. Standards errors have been adjusted by a factor of 1.2 in high quality studies (all study designs), 2 in medium quality before-and-after studies, and 3 in low quality before-and-after studies. In case-control or cross-section studies, standard errors were adjusted by a factor of 3 medium quality studies and a factor of 5 in low quality studies.

An internal comparison group refers to the use of daytime accidents as comparison group when estimating the effect on lighting. For example, assume that there were 80 accidents in daytime and 55 in darkness before lighting was installed, and that the number of accidents in daytime increased to 84 and the number of accidents in darkness declined to 39 after lighting was installed. The resulting effect would then be estimated to: (39/55)/ (84/80) = 0.675.

This design does not control for two potential confounding factors: (1) Long-term trends in the proportion of accidents occurring in darkness, and (2) Regression-to-the-mean, in particular with respect to an abnormally high proportion of accidents in darkness. To some extent, both these confounding factors can be controlled for by using an external comparison group, i.e., intersections where lighting has not been installed. Suppose, for example, that for intersections where lighting was not installed, the following numbers were observed: Daytime before = 112; daytime after = 119; darkness before = 58; darkness after = 54. Then, in the comparison group, the odds ratio would be: (54/58)/ (119/112) = 0.876. The adjusted estimate of effect (ratio of odds ratios) would be: 0.675/0.876 = 0.771.

Exhibit 6-39: Resources examined to investigate the safety effect of illumination in highway work zones

DOCUMENT	DESCRIPTION	COMMENT
(CH2M HILL, "NCHRP Report 500 Volume 19: A Guide for Designing Safer Work Zones - DRAFT." Washington, D.C., Transportation Research Board, National Research Council, (2004))	Synthesis of information including recent literature, contact with state and local agencies throughout the United States, and federal programs.	DRAFT – to be reviewed when final is published.
(Bernhardt, K. L., Virkler, M. R., and Shaik, N. M., "Evaluation of Supplementary Traffic Control Measures for Freeway Work-Zone Approaches." Washington, D.C., 80th Transportation Research Board Annual Meeting, (2001))	Report describing the results of the testing of three individual traffic control devices.	Not relevant for this section. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*17*) (Elvik, R., "Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure." Transportation Research Record 1485, Washington, D.C., Transportation Research Board, National Research Council, (1995) pp. 112-123.)	A meta-analysis of 37 studies, containing a total of 142 results from 1948 to 1989.	Added to synthesis.
(Stout, D., Graham, J., Bryant-Fields, B., Migletz, J., Fish, J., and Hanscom, F., "Maintenance Work Zone Safety Devices Development and Evaluation." SHRP-H-371, Washington, D.C., Strategic Highway Research Program, National Research Council, (1993))	Report presenting the findings of tests and evaluations of several new work safety zone devices.	No AMFs. Not added to synthesis.
(Dudek, C. L., Huchingson, R. D., Creasey, F. T., and Pendleton, O., "Field Studies of Temporary Pavement Marking at Overlay Project Work Zones on Two-Lane, Two-Way Rural Highways." Transportation Research Record 1160, Washington, D.C., Transportation Research Board, National Research Concil, (1988) pp. 22-34.)	Report based on field studies conducted to compare the safety and operational effectiveness of differently spaced broken line pavement markings in work zones.	Not relevant for this section. Not added to synthesis.

Exhibit 6-40 shows summary estimates of the effects of lighting on accidents (it is important to note that AMFs in this exhibit are for all conditions, not just work zones). This summary is based on (*17*) and was updated by Elvik for NCHRP Project 17-27. Safety effects are stated as odds ratios. Uncertainty in summary estimates of effect is stated as adjusted standard error. All estimates of effect refer to accidents in darkness only.

Two sets of summary estimates of effect are presented in Exhibit 6-40. The first set is based on conventional meta-analysis. The second set has been generated from coefficients estimated in meta-regression analysis. In theory, the meta-regression estimates are superior to the conventional summary estimates, since meta-regression controls for more confounding factors or imbalance in the distribution of estimates across moderator variables (a moderator variable is any variable that influences the size of the effect of a measure on accidents).

Only estimates that specify accident severity have been used. Estimates referring to “all” accidents, which is usually a mixture of injury accidents and property-damage-only accidents have been discarded. The number of estimates underlying each summary estimate is stated in parentheses.

All summary estimates of effect, both those based on the conventional meta-analysis and those based on meta-regression, indicate that illumination reduces the number of accidents. There is a systematic pattern in summary estimates of effect: the largest effect is found for fatal accidents, the smallest effect is found for property-damage-only accidents. There is little variation in effects between various types of traffic environment (rural, urban, freeways). This applies both to the conventional summary estimates and to the summary estimates based on meta-regression. It is therefore clear that illumination reduces the number of accidents in darkness, in particular fatal accidents.

Some of the conventional summary estimates are based on very few estimates of effect. These summary estimates have large standard errors. In subsets that contain few estimates of effect, the standard errors are smaller for the meta-regression summary estimates than for the conventional summary estimates. The meta-regression summary estimates indicate larger effects on accidents in nearly all cases than the conventional summary estimates. The reasons for this are not clearly evident. It is surprising since the effects attributed to road safety measures often tend to get smaller when at study controls for more confounding or contextual variables. In this case, the opposite pattern is found.

Exhibit 6-40: Summary estimates of the effects on accidents of public lighting

Road type & setting	**Accident severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Summary estimates based on conventional meta-analysis			
All types of highway	Fatal accidents (18)	0.313	0.361
	Injury accidents (85)	0.717	0.056
	PDO-accidents (19)	0.825	0.072
Rural highways	Fatal accidents (2)	0.265	0.720
	Injury accidents (21)	0.802	0.124
	PDO-accidents (3)	0.696	0.426
Urban highways	Fatal accidents (13)	0.365	0.515
	Injury accidents (46)	0.685	0.073
	PDO-accidents (16)	0.840	0.075
Freeways	Fatal accidents (3)	0.274	0.712
	Injury accidents (20)	0.728	0.121
	PDO-accidents (2)	0.678	0.256
Summary estimates based on meta-regression analysis			
All types of highway	Fatal accidents	0.261	0.285
	Injury accidents	0.577	0.208
	PDO-accidents	0.590	0.217
Rural highways	Fatal accidents	0.269	0.273
	Injury accidents	0.594	0.192
	PDO-accidents	0.607	0.202
Urban highways	Fatal accidents	0.260	0.257
	Injury accidents	0.576	0.169
	PDO-accidents	0.589	0.180
Freeways	Fatal accidents	0.253	0.269
	Injury accidents	0.559	0.187
	PDO-accidents	0.572	0.197

6.2.4.2. Weather [Future Edition]

In future editions of the HSM, the safety effects of weather conditions on the work zone and road users may be discussed here. Weather conditions may include drainage, warning messages for mist, fog, and rain ahead, as well snow and ice-clearing policies for the work zone. No potential resources for this section have been identified.

6.3. Bridges [Future Edition]

Future editions of the HSM may provide information on the safety effect of various bridge design and operational characteristics in this section. Elements of interest may include deck length and width (number of lanes), bridge railings or shoulders, medians, horizontal and vertical alignment, approach to bridges, bridge deck material, signage, pavement markings, surface condition of bridge deck (possibly related to weather), illumination, provisions for pedestrians and cyclists, etc. Potential resources are listed in Exhibit 6-41.

Exhibit 6-41: Potential resources on the safety of bridges

DOCUMENT
(Ferrara, T. C. and Gibby, A. R., "Statewide Study of Bicycles and Pedestrians on Freeways, Expressways, Toll Bridges and Tunnels." FHWA/CA/OR-01/20, Sacramento, California Department of Transportation, (2001))
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))
(Lee, J. and Mannering, F., "Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management." WA-RD 475.1, Olympia, Washington State Department of Transportation; (1999))
(Friar, S. and Decker, R., "Evaluation of a Fixed Anti-Icing Spray System." Transportation Research Record, No. 1672, Washington, D.C., Transportation Research Board, National Research Council, (1999) pp. 34-41.)
(Perrillo, K., "The Effectiveness and Use of Continuous Shoulder Rumble Strips." Albany, N.Y., Federal Highway Administration, (1998))
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))
(Miaou, S. P., "Measuring the Goodness of Fit of Accident Prediction Models." FHWA-RD-96-040, McLean, Va., Federal Highway Administration, (1996))
(Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III - Cross Sections." FHWA-RD-91-046, Washington, D.C., Federal Highway Administration, (1992))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

6.4. Tunnels [Future Edition]

In future editions of the HSM, this section may discuss tunnel width (number of lanes), medians, horizontal and vertical alignment, shoulders, escape routes, shoulders for emergency pull-overs, illumination, signage, traffic control devices, restricted-width tunnels (single lane tunnel for two-way traffic), reversible lanes in tunnels, height of tunnels (vehicle type), and accommodation of cyclists and pedestrians. Potential resources are listed in Exhibit 6-42.

Exhibit 6-42: Potential resources on the safety of tunnels

DOCUMENT
(Ferrara, T. C. and Gibby, A. R., "Statewide Study of Bicycles and Pedestrians on Freeways, Expressways, Toll Bridges and Tunnels." FHWA/CA/OR-01/20, Sacramento, California Department of Transportation, (2001))
(McLean, J., "Practical Relationships for the Assessment of Road Feature Treatments - Summary Report." ARR 315, Vermont South, Australia, ARRB Transport Research Ltd, (1997))

6.5. Two-way Left-turn Lanes

A two-way left-turn lane (TWLTL) is a common access management treatment used for many years on urban and suburban arterials with commercial development. These lanes are sometimes called continuous center left-turn lanes (CCLTLs).

A TWLTL is a special lane in the center of the highway reserved for vehicles making mid-block left-turns (between intersections) into or out of driveways. A TWLTL may also be carried through intersections with minor streets that are not controlled for the major traffic flow. The lane provides a deceleration and storage area for vehicles making these left-turns and is used by drivers traveling in either direction. The use of TWLTLs in the center of an urban or suburban four-lane road is well established. Since about 1990, TWLTLs have been used in the center of two-lane roads. TWLTLs are also used on six-lane roads and in rural and urban fringe areas.

TWLTLs target left-turn accidents into and out of driveways, in particular rear-end and sideswipe accidents.

TWLTLs are intended to reduce delays and conflicts caused by turning traffic and to improve safety by protecting drivers wanting to turn left from through vehicles while waiting for a gap in the traffic. However, challenges may still arise:

- Where drivers increase their speed on the through lanes due to the left-turning traffic being removed;
- Where a through lane is an HOV lane which may carry little traffic, encouraging drivers to risk crossing it even when their view is blocked as they do not expect a vehicle to be coming;
- In urban areas where the TWLTL means that pedestrians have further to walk across the road;
- In urban areas where pedestrians may treat the TWLTL as a refuge area;
- Where traffic volumes increase so that traffic backs up in the turning lane, especially if there are many driveways and the backed up traffic impedes vehicles wanting to turn left in the opposite direction;
- Where the driveway entrance is poorly designed and cannot readily accommodate the turning traffic which may then slow down or even stop as it crosses the through lanes;
- Where driveways are not clearly marked and conspicuous so that drivers do not know well in advance whether a left-turn is feasible; and
- Where drivers use the TWLTL for passing. Fitzpatrick et al. (*42*) cite Harwood and St. John who found that 0.4% were involved in illegal passing of vehicles. A TWLTL that leads to the loss of a passing lane needs careful evaluation; and
- Several states in the southeastern United States have constructed seven-lane urban arterials where one lane is a TWLTL. On these roads, problems may arise because drivers may cross six or seven lanes to enter or exit a business.

This section examines the impact of driveway density and the safety effectiveness of TWLTLs on rural two-lane roads, rural multi-lane highways, and urban and suburban arterials.

Exhibit 6-43: Resources examined on the relationship between two-way left-turn lanes and safety on urban and suburban arterials.

DOCUMENT	DESCRIPTION	COMMENT
(Persaud, B., Lyon, C., Eccles, K., Lefler, N., Carter, D., and Amjadi, R., "Safety Evaluation of Installing Center Two-Way Left-Turn Lanes on Two-Lane Roads," Report No. FHWA-HRT-08-042, Federal Highway Administration, Washington, D.C., (2008))	The study discusses the safety effectiveness of TWLTLs in reducing total, injury, and rear-end crashes.	Added to synthesis. Includes AMF.
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	AMF estimates based on sources reviewed by Hauer (2000). Not added to synthesis.
(*43*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The study discusses TWLTLs as one of many potential countermeasures for reducing the number of head-on fatal crashes	Limited qualitative and quantitative information. Added to synthesis. No AMFs.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Forbes reviewed eight studies none of which post-dated the studies reviewed by Hauer or Harwood et al. in 2000.	No additional quantitative information. Not added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study lists and briefly discusses many potential low-cost safety countermeasures for two-lane and three-lane roadways.	Limited qualitative and quantitative information. Not added to synthesis.
(*44*) (Hauer, E., "The Median and Safety." (2000))	The report provides detailed reviews of the safety effects of six major approaches to median design including TWLTLs.	Added to synthesis.
(*45*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	The study presents an algorithm for predicting the safety performance on rural two-lane highways. A panel of experts developed the AMFs used in the accident prediction algorithm.	Added to synthesis. Includes AMF.
(Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999))	The report discusses selected access management techniques.	Limited quantitative information. Not added to synthesis as main focus was access management and TWLTL work superseded by Harwood et al., 2000.
(Castronovo, S., Dorothy, P. W., and Maleck, T. L., "An Investigation of the Effectiveness of Boulevard Roadways." Washington, D.C., 77th Transportation Research Board Annual Meeting, (1998))	The study compared accident rates on roadways with TWLTLs with accident rates on boulevards with divided directional cross-over median designs.	Limited information. Not added to synthesis No AMFs.

DOCUMENT	DESCRIPTION	COMMENT
(Bonneson, J. A. and McCoy, P. T., "Effect of Median Treatment on Urban Arterial Safety: An Accident Prediction Model." Transportation Research Record 1581, Washington, D.C., Transportation Research Board, National Research Council, (1997) pp. 27-36.)	The study used crash data to model the relationship between crashes and median treatment including two-way left-turn lanes and raised medians on urban arterials.	Reference suggested by NCHRP 17-18(4). Included in Hauer's review in 2000. Not added to synthesis.
(*46*) (Harwood, D. W., "NCHRP Report 330: Effective Utilization of Street Width on Urban Arterials." Washington, D.C., Transportation Research Board, National Research Council, (1990))	The report reviews the literature on urban arterial street width. It includes a review of TWLTLs and safety.	Limited qualitative and quantitative information. Added to synthesis. No AMFs.
(Harwood, D. W., "NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways." Washington, D.C., Transportation Research Board, National Research Council, (1986))	The study investigated and compared the safety (and other) characteristics of selected multi-lane road types in suburban areas.	Reference suggested by NCHRP 17-18(4).This study is reviewed in Harwood 1990 and Hauer 2000.Not added to synthesis.
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))	Synthesis of practices up to 1982.	Not added to synthesis. No AMFs.

The definition of target accidents for TWLTLs is important in studies of the safety effectiveness of TWLTLs. Hauer points out that as TWLTLs are designed to prevent accidents at access points, mainly left-turn in and out accidents, AMFs for TWLTLs should apply only to driveway-related accidents (not to all accidents on the road segment) and only to the in and out left-turn accidents at driveways (*44*). Hauer considered that as about half of all driveway-related accidents are associated with in and out left-turns, TWLTLs target about half of driveway-related accidents.

Regarding target accidents, Harwood comments that "It is likely that TWLTLs are more effective when installed at sites with a high proportion of rear-end and angle accidents (as they usually are)" (page 13) (*46*). Harwood also points out that head-on accidents are not a major concern after implementation of TWLTL. Harwood found that the literature on three- and five-lane TWLTLs "universally discounts the possibility of substantial increases in head-on accidents" (page 13) and that "head-on accidents usually decrease with TWLTL installation, although not as much as other accident types such as rear-end accidents" (page 13).

Studies are likely to provide different estimates of accident reduction depending on access density and the traffic volume of in and out left-turns at the access points. Hauer reviewed studies from 1964 to 2000, but found no studies that recognized the importance of driveway density or frequency of in and out left-turns at the access points of access-point related left-turns and the proportion of left-turn accidents (*44*). Most studies of the safety effectiveness of TWLTLs report all accidents, not just the target accidents.

Studies have investigated the safety effectiveness of TWLTLs using various approaches. These include comparing TWLTLs with other median treatments (undivided roadways or raised medians), comparing three, five and seven-lane roadways, examining various types of TWLTL installation including restriping or road widening, and for divided or undivided roadways.

Hauer points out that studies' findings on the safety effectiveness of TWLTLs vary because of methodological problems and inadequacies, and because the researchers did not include only TWLTL target accidents (*44*).

Neuman et al.'s 2003 study of TWLTLs for two- and four-lane roads found that although TWLTLs are "fairly widely used", they have "not been sufficiently evaluated to be considered 'proven' " (page V-16) (*43*). The authors concluded that, "there are no truly valid estimates of the effectiveness of such conversions [to TWLTLs] based on sound before/after studies for a two-lane road… Precise estimates of effectiveness should be developed" (page V-16) (*43*).

The safety effects of TWLTLs in relation to pedestrians are discussed in Section 3.3.

Treatment: Provide two-way left-turn lane

Rural two-lane roads

Although TWLTLs are generally associated with urban and suburban arterials, the best AMF estimates are for rural two-lane highways using Harwood et al.'s 2000 approach and a detailed consideration of driveway density on rural two-lane highways (*45*).

A panel of experts concluded that TWLTLs are inappropriate where there are less than three driveways per kilometer (five driveways per mile). If the driveway density is less than three driveways per kilometer, the AMF for TWLTL installation is 1.00.

Where driveway density is three or more driveways per km (five driveways per mi), Harwood et al.'s AMF for the installation of a TWLTL is given in Equation 6-4 (*45*) (page 40).

Equation 6-4: AMF for the installation of a TWLTL on rural two-lane highways where driveway density is three or more driveways per km (five driveways per mi) (45)

$$AMF = 1 - 0.7\, P_D\, P_{LT/D}$$

where

P_D = driveway-related accidents as a proportion of total accidents

$= (0.0047DD + 0.0024DD^2) / (1.199 + 0.0047DD + 0.0024DD^2)$; and

$P_{LT/D}$ = left-turn accidents susceptible to correction by a TWLTL as a proportion of driveway-related accidents (estimated by the expert panel to be 0.5)

The AMF applies to left-turn accidents in and out of driveways; it does not apply to non-driveway-related accidents and non-left-turn accidents at driveways.

The standard error for the function is not reported.

The function is based on Hauer's work (*44*), but has been altered to give a more conservative result than Hauer's original formulation. (For example, whereas Harwood et al.'s AMF for 10 driveways per mile is 0.93, Hauer's original AMF for 10 driveways per mile was 0.85.) Using Harwood et al.'s approach, the AMF for a TWLTL on a rural two-lane highway with 25 driveways per mile is 0.80, an accident reduction of 20% for the target accidents (left-turn in and out accidents at driveways) (*45*).

If the driveway density along a rural two-lane road is unknown, Exhibit 6-44 presents alternative AMFs that can be used to estimate the safety effects of installing a TWLTL along the roadway, Persaud et al. (2008) used the Empirical Bayes (EB) methodology for observational before-after studies to evaluate the safety effectiveness of TWLTLs on rural two-lane roads. Data were collected from four states (*60*). A method correction factor of 1.2 was used to adjust the standard errors from this study. Persaud et al. noted that future research on the impacts of intersection and driveway density and on differentiating the effect of the two installation methods, restriping versus widening, could provide additional insights into the effectiveness of this measure.

Exhibit 6-44: AMFs for TWLTLs on rural two lane roads (60).

Treatment/ Element	Setting Road Type	Accident type & severity	Index of Change, $t_{adjusted}$	Estimate of Std. Error, s
Provide two-way left-turn lane (TWLTL)	Rural Two-lane	Total accidents; all types	0.64	0.04
		Injury accidents; all types	0.65	0.08
		Total accidents; rear-end	0.53	0.05

Rural multi-lane highways; Freeways; Expressways

No studies found.

Urban and suburban arterials

Hauer found that most studies of TWLTLs suggest an AMF for urban and suburban arterials of about 0.70. He concludes that the best AMF estimates available for all accident types range from 0.70 to 0.90 (*44*). (Although the standard error for these AMF estimates is unknown, the level of confidence is likely to be "medium-high" as this work contributed to the calculation of the AMFs for rural two-lane highways given above.)

Harwood reviewed studies of TWLTL design on urban arterials in 1990 (*46*). The target accidents in this review are unclear but probably included all accidents rather than just left-turn accidents at driveways. Based on a literature review by Harwood "the safety effectiveness of converting from the two-lane undivided to the three-lane TWLTL design alternative is expected to be in the range of 11 to 35% accident rate reduction" (page 25). In the case of five-lane cross-sections with a TWLTL, Harwood reports that the studies "generally concluded that TWLTLs reduce accident rate by from 19 to 35%" (page 27). Standard errors were not reported and could not be calculated for these AMFs.

Persaud et al. (2008) evaluated the safety effectiveness of TWLTLs installed on several urban sites (*60*). They found the safety effects to be negligible and suggested that potential sites in this environment should be carefully selected and that future research may be necessary to identify circumstances most favorable for urban installations.

Although several studies of the safety effect of TWLTLs on urban and suburban arterials indicate some safety benefit, an AMF cannot be derived. Further research is necessary in order to quantify the safety effect of TWLTLs on urban and suburban arterials.

6.6. Passing and Climbing Lanes

A passing lane is a lane provided on two-lane two-way rural roads to increase overtaking opportunities and reduce delays. Passing lanes are provided where problems arise on level or rolling terrain. (Climbing lanes are provided to overcome delays caused by slow moving vehicles on steep upgrades.) It is generally more cost-effective to improve passing opportunities than to reconstruct existing roads. There are several low-cost strategies for adding passing opportunities:

- Passing lanes;
- Short four-lane sections - passing lanes are provided in both directions of travel;
- Climbing lanes - provided to overcome delays caused by slow moving vehicles on steep upgrades;
- Turnouts - short auxiliary lanes used in winding, mountainous areas; and
- Shoulder use sections - shoulders are provided for disabled vehicles which need to stop or recover. Though driving on shoulders is usually illegal, shoulders may be used by slow moving vehicles in some areas to allow other vehicles to pass. Some shoulders are signed where shoulder use is allowed.

These strategies are shown in Exhibit 6-45.

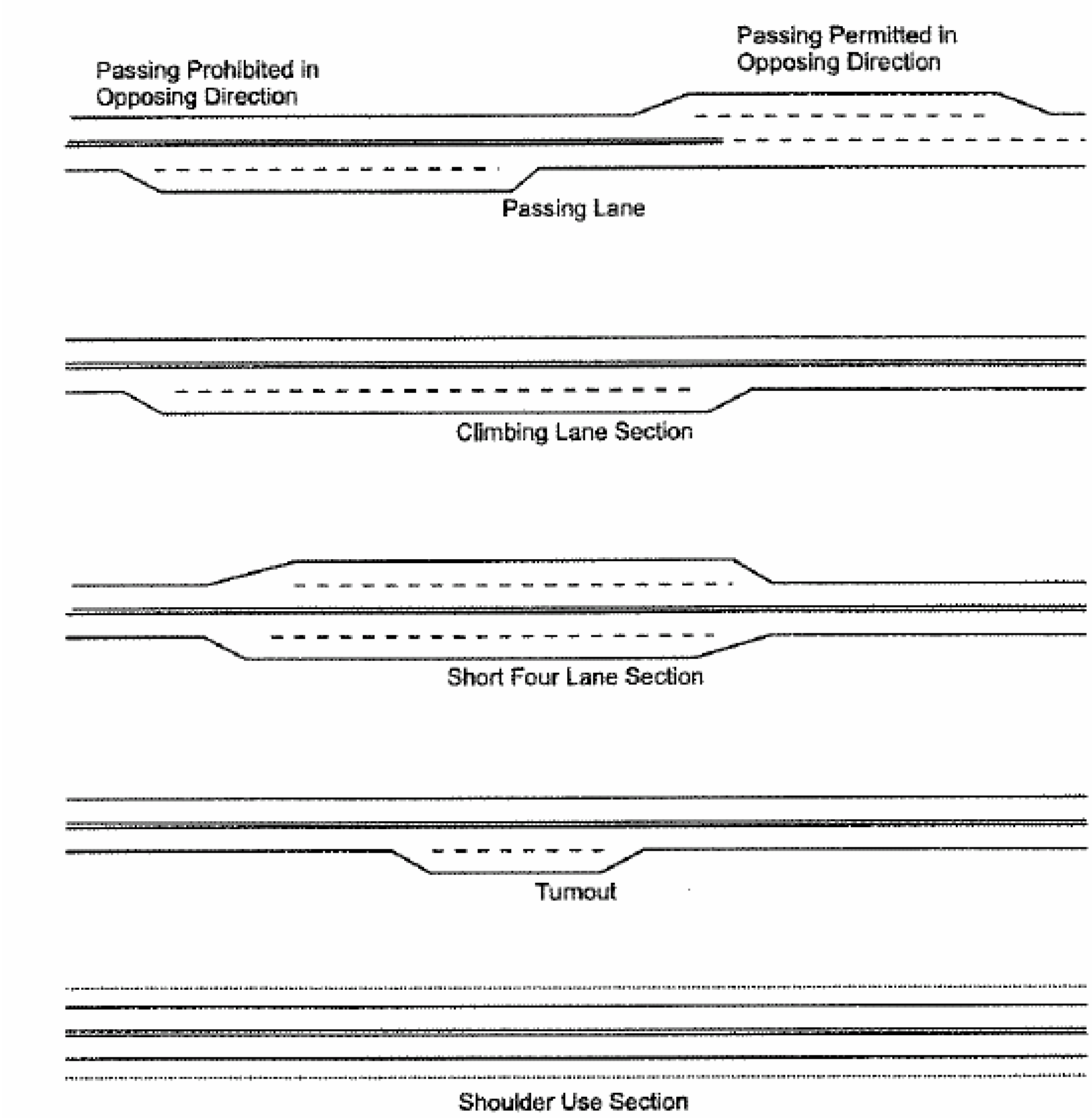
The length of a passing lane varies; the optimal length is usually 0.8 to 3.23 km (0.5 to 2.0 mi) (*2*). Passing lanes may be isolated and designed to alleviate a particular bottleneck problem or may be provided at regular intervals to improve overall traffic operations along a road segment.

Passing lanes are designed to minimize vehicle interactions and reduce hazardous situations by providing motorists with safe passing opportunities. Most rural two-lane highways carry relatively little traffic and experience few operational problems. However, safety and operational problems may arise where traffic volume becomes heavy. Additional problems include poor sight distance, lack of passing opportunities, the percentage of trucks and slow moving vehicles, the range of driving speeds, and rolling or steep terrain. Where platoons develop, delays and frustration may lead to illegal passing and passing-related accidents.

Passing lanes may also be used to preserve community character and scenic areas. Passing lanes are particularly useful in restricted corridors where only one road is available. Refer to the AASHTO Policy on Geometric Design of Highways and Streets for details on the design and placement of passing lanes (*2*).

Passing lanes target passing-related crashes such as passing-related head-on, same-direction sideswipe, and opposite-direction sideswipe crashes. Crashes that can be related to passing are a very small proportion of all crashes and the safety aspects of passing and climbing lanes have not been the subject of much research. Passing-related head-on crashes are “a relatively low percentage of all head-on crashes” (page V-21) (*43*). Passing lanes may also reduce crashes associated with vehicles traveling in platoons, but the safety benefits to the whole corridor affected by the passing lane installations are not known.

Exhibit 6-45: Typical treatments for adding passing opportunities on two-lane highways



Climbing lanes are short roadway segments that allow slow moving vehicles to “climb” grades while other vehicles pass. Climbing lanes are used where heavy vehicles such as trucks and recreational vehicles slow down due to gradient and may create potential conflicts with other vehicles.

Climbing lanes allow traffic platoons which have formed behind slower vehicles to dissipate in a safer manner than using an oncoming traffic lane to facilitate a passing maneuver. Alternatively, climbing lanes provide an improvement on highway sections which may not meet warrants for adding additional lanes, but which show a demand for overtaking that exceeds the available opportunities and deterioration of levels-of-service in terms of reduced speeds.

Climbing lanes are added to the upgrade side of a two-lane highway. The center and downgrade outer lanes operate as a conventional two-lane highway. The climbing lane should be immediately recognizable. Signs may include "SLOWER TRAFFIC KEEP RIGHT" or “TRUCKS USE RIGHT

LANE" to direct slow moving vehicles into the climbing lane. The centerline of the normal two-lane roadway is clearly marked. Climbing lanes generally continue over the vertical curve crest so that vehicles may gain speed before merging.

Justification for providing climbing lanes may be based on safety performance of the roadway, lack of sight distance, traffic volume and composition, gradient, speed, speed reduction, speed differential, delay or platooning, level-of-service and economics. For example, some jurisdictions require climbing lanes on grades steeper than 2% and longer than 500 m. The American Association of State Highway and Transportation Officials (AASHTO) states that a minimum truck speed reduction of 16 km/h (10 mph) justifies the addition of climbing lanes (*2*).

It is generally expected that climbing lanes reduce the number of accidents that arise from speed differential problems and resulting conflicts between slow moving vehicles and passing vehicles. The main target accidents are rear-end and same direction sideswipe accidents. Additional concerns include head-on and opposite direction sideswipe accidents.

A slow moving vehicle turnout is not an auxiliary lane. AASHTO describes a turnout as "a widened, unobstructed shoulder area that allows slow-moving vehicles to pull out of the through lane to give passing opportunities to following vehicles" (*2*). A turnout may be provided on roadways where opportunities to pass slow moving vehicles are limited and where the cost of providing a full auxiliary lane would be prohibitive (Exhibit 6-45).

To determine the safety effects of climbing lanes (or turnouts), it is necessary to compare the number of crashes on roadway segments with climbing lanes (or turnouts) with the number of crashes on similar roadway segments without climbing lanes (or turnouts).

This section discusses the safety effect of passing lanes and climbing lanes on rural two-lane roadways. The use of short four-lane sections and shoulder use sections as passing lanes is included here; along with climbing lanes and turnouts. Current knowledge is limited, and there is a need to confirm the AMFs available for passing lanes and short four-lane sections and to quantify the safety impact of passing lane length, passing lane spacing, ADT and traffic mix (truck percentage), grades, horizontal curvature, sight distance, tapers and merges for passing lanes.

The safety impacts of the following passing lane-related elements were not found in current literature, and may be added to future editions of the HSM: three-lane alternate passing design, design elements (such as passing lane length, passing lane spacing, grades, horizontal curvature, sight distance, tapers and merges, shoulders), traffic operational elements (such as corridor speed, signage and pavement markings), ADT and traffic mix (truck percentage), the presence of intersections and /or access points/driveways on passing lane sections, and the impact on the roadway as a whole (corridor approach).

Future HSM editions may cover the safety effect of climbing lanes and turnouts in relation to traffic volumes, traffic mix (truck percentage), different grades, corridor speed and speed differentials, horizontal curvature, signage, markings, advance signage of passing opportunity and the impact on the roadway as a whole (beyond the length of the facility itself).

Exhibit 6-46: Resources examined on the safety of passing and climbing lanes

DOCUMENT	DESCRIPTION	COMMENT
(Elvik, R. and Vaa, T., "Handbook of Road Safety Measures." Oxford, United Kingdom, Elsevier, (2004))	The book provides a systematic overview of the effects of road safety measures (translated from 1997 Norwegian edition, partly updated).	No information on passing lanes. Not added to synthesis.

DOCUMENT	DESCRIPTION	COMMENT
(*43*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., McGee, H., Prothe, L., Eccles, K., and Council, F. M., "NCHRP Report 500 Volume 4: A Guide for Addressing Head-On Collisions ." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The study discusses passing lanes as one of many potential countermeasures for reducing the number of head-on fatal crashes.	Added to synthesis. Provides percent reduction in crashes based on literature review.
(*45*) (Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways." FHWA-RD-99-207, McLean, Va., Federal Highway Administration, (2000))	The study presents an algorithm for predicting the safety performance on rural two-lane highways. A panel of experts developed the AMFs used in the accident prediction algorithm.	Climbing lanes mixed with passing lanes. Added to synthesis.
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))	The study lists and briefly discusses many potential low-cost safety countermeasures for two-lane and three-lane roadways.	Not added to synthesis. Values reported by Neuman et al., 2003.
(Curren, J. E., "NCHRP Report 369: Use of Shoulders and Narrow Lanes to Increase Freeway Capacity." Washington, D.C., Transportation Research Board, National Research Council, (1995))	The study evaluated strategies to increase the capacity of urban freeways by using shoulders with and without narrow lanes.	No information. Not added to synthesis.
(Taylor, W. C. and Jain, M. K., "Warrants for Passing Lanes." Transportation Research Record 1303, Washington, D.C., Transportation Research Board, National Research Council, (1991) pp. 83-91.)	Used a simulation model to study the operational benefits of passing lanes. The study compared accident rates on sections with and without passing lanes, but these sections are likely to differ considerably in basic characteristics.	Not added to synthesis.
(*48*) (St.John, A. D. and Harwood, D. W., "Safety Considerations for Truck Climbing Lanes on Rural Highways." Transportation Research Record 1303, Washington, D.C., Transportation Research Board, National Research Council, (1991) pp. 74-82.)	The paper explored the problem of warrants for climbing lanes by investigating slow moving trucks and grade. Only speed related accidents were considered.	Reference suggested by NCHRP 17-18(4). No AMFs. Limited qualitative information added to synthesis.
(47) (Khan, A. M., Holtz, N. M., and Yicheng, Z., "Cost-Effectiveness of Climbing Lanes: Safety, Level of Service and Cost Factors." TDS-90-08, Downsview, Ontario, Canada, Ontario Ministry of Transportation, (1990))	The study examines the role of climbing lanes in reducing the problems created by slow vehicles. It includes a summary of safety aspects.	Reference suggested by NCHRP 17-18(4). Limited qualitative/quantitative information. Added to synthesis.
(ADI Limited, "Passing Manoeuvres and Passing Lanes: Design, Operational & Safety Evaluations." Ottawa, Ontario, Canada, Transport Canada, (1989))	The report reviews the operation and safety of passing lanes on two-lane two-way highways.	The findings were reviewed in Harwood et al., 2000 and Fitzpatrick et al., 2000. Not added to synthesis.

Treatment: Add passing lanes or short four-lane sections

Rural two-lane roads

Three groups of authors have recently reviewed and synthesized the findings of passing lane studies: Neuman et al. (2003) (*43*), Harwood et al. (2000) (*45*), and Fitzpatrick et al. (2000) (*42*).

Neuman et al.'s synthesis (*43*) summarizes the results of the studies reviewed in all three publications. The base condition for an AMF for a passing lane is the absence of the passing lane. The AMF for short four-lane sections (side by side passing lanes provided in opposite directions on the same roadway section) does not apply to extended four-lane sections. Estimates of the standard error of the AMFs in Exhibit 6-47 are not reported and not calculable.

Exhibit 6-47: AMFs for passing lanes, short four-lane sections and shoulder use sections on rural or suburban two-lane roads (43)

Design alternative	All severities	Fatal and injury
Passing lanes	0.75	0.70
Short four-lane sections	0.65	0.60
Shoulder use sections	No known statistically significant effect	

The AMFs in Exhibit 6-47 for total crashes appear to be the same as those reported by Harwood et al. (*45*) and Fitzpatrick et al. (*42*).

Neuman et al. commented that it is possible that shoulder treatments may have been a confounding factor at some sites studied if the shoulder treatments were constructed simultaneously with passing lanes or short four-lane sections (*43*).

Neuman et al. pointed out that passing lanes or short four-lane sections have been "fairly widely used", but passing lanes have "not been sufficiently evaluated to be considered 'proven'" (V-21) (*43*). This suggests that additional studies are needed to provide methodologically and statistically sound measures of safety effectiveness.

Both Neuman et al. and Harwood et al. indicate that passing lanes are known to affect traffic 3 to 8 mi (5 to 13 km) downstream of the passing lane, but the effect has not been quantified in safety terms (*43*) (*45*).

Rural multi-lane highways; Freeways; Expressways; Urban and suburban arterials

No studies found.

Discussion: Add a climbing lane

Rural two-lane roads

Harwood et al. found that the AMF "for a conventional passing or climbing lane" in one direction on a rural two-lane road is 0.75 for total accidents (page 39); an estimate of standard error cannot be determined for this value (*45*). This is the same value noted by Neuman et al. for passing lanes (*43*). Due to the combination of passing and climbing lanes in this value, further research is needed to determine the safety impact of climbing lanes alone.

Kahn et al.'s 1990 summary of the research available also concluded that "climbing/passing lanes have been credited with a reduction in accident rates by 25% or higher as compared with untreated two-lane sections" (page 43) (*47*). The studies reviewed ranged from a reduction of 11% to a reduction of 42%. The standard error for this value could not be calculated. Further research is needed to determine the safety impact of climbing lanes.

Speed differentials in relation to climbing lanes have received some attention. St. John and Harwood's 1991 study noted that the role of slow moving trucks in creating potential for crashes was not quantified (page 74) (*48*). Khan et al. refer to Homburger's work in 1987 and Glennon's work in 1970 as examples of studies that have shown that accidents happen more frequently and are more severe as speed differentials increase (page 41) (*47*).

Information in the current literature on safety effects of the design elements of climbing lanes is limited. Kahn et al. noted that “Inadequate sight distance prior to the lane drop creates a safety hazard” (page 43) and that “Lane addition (diverge) and (merge) areas do not represent any marked safety hazards”, (page 43) but gave no additional information (*47*).

Therefore, the only AMF estimate found in the current literature for adding climbing lanes (in combination with passing lanes) on a rural two-lane road is 0.75 for all accident types and severities; an estimate of standard error for this AMF could not be determined.

Rural multi-lane roads; Freeways; Expressways; Urban and suburban arterials

Not applicable.

6.7. Emergency Escape Ramps [Future Edition]

Long downgrades may cause trucks to require emergency braking and stopping by means of entering an emergency escape ramp. As defined in the AASHTO Policy on Geometric Design, emergency escape ramps “provide a location for out-of-control vehicles, particularly trucks, to slow and stop away from the main traffic stream…generally the result of a driver losing braking ability either through overheating of the brakes due to mechanical failure or failure to downshift at the appropriate time” (*2*).

Crashes resulting from a truck’s loss of control and inability to stop tend to be severe. The safety effect of emergency escape ramps will be discussed in this section in future editions of the HSM. The safety impacts of different emergency escape ramp designs such as sandpile, ascending grade arrester bed, horizontal grade arrester bed, or descending grade arrester bed may be discussed. Potential resources were not found for this section.

6.8. Emergency Crossovers [Future Edition]

To be addressed in future editions.

6.9. Rest Stops [Future Edition]

Future editions of the HSM may provide discussion in this section on the safety effect of providing rest stops on long stretches of highway. Potential resources are listed in Exhibit 6-48.

Exhibit 6-48: Potential resources on the safety of rest stops

DOCUMENT
(Knipling, R. R., Waller, P., Peck, R. C., Pfefer, R., Neuman, T. R., Slack, K. L., and Hardy, K. K., "NCHRP 500 Report Volume 13: A Guide for Addressing Collisions Involving Heavy Trucks." Washington, D.C., Transportation Research Board, National Research Council, (2003))

6.10. High Occupancy Vehicle Facilities [Future Edition]

High occupancy vehicle (HOV) lanes promote the utilization of highway infrastructure in a more cost effective manner by minimizing the number of vehicles traveling and increasing the number of occupants per vehicle. The safety effects of separating this traffic from the mixed traffic lanes will be discussed in this section in future editions of the HSM.

In future editions of the HSM, this section may discuss the traffic control devices and operational elements specific to HOV lanes or other special denomination lanes (e.g., bus-only lanes), and the related safety performance. Some elements that may be of interest include: the design of diverge and merge access points to HOV facilities, the type of separation between HOV lanes and general traffic, speed differentials, reversible HOV lanes, the mix of traffic permitted, and provision on the left or right side of the highway. Potential resources are listed in Exhibit 6-49.

Note that bicycle lanes and shared bike/bus lanes are discussed in Section 3.3.

Exhibit 6-49: Potential resources on the relationship between HOV lanes and safety

DOCUMENT
(Curren, J. E., "NCHRP Report 369: Use of Shoulders and Narrow Lanes to Increase Freeway Capacity." Washington, D.C., Transportation Research Board, National Research Council, (1995))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

6.11. Reversible Roadways and Lanes [Future Edition]

The safety effects of using reversible roadways or lanes may be discussed in future editions of the HSM. Elements that may influence the safety performance of reversible roadways or lanes include signage, pavement markings, traffic operations, access points and access management. Potential resources are listed in Exhibit 6-50

Exhibit 6-50: Potential resources on the relationship between reversible lanes and safety

DOCUMENT
(Harwood, D. W., "NCHRP Report 330: Effective Utilization of Street Width on Urban Arterials." Washington, D.C., Transportation Research Board, National Research Council, (1990))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

6.12. Frontage Roads [Future Edition]

In future editions of the HSM, this section may discuss the safety effect of various elements of frontage roads. Potential resources are listed in Exhibit 6-51.

Exhibit 6-51: Potential resources on the safety of frontage roads.

DOCUMENT
(Gluck, J., Levinson, H. S., and Stover, V., "NCHRP Report 420: Impact of Access Management Techniques." Washington, D.C., Transportation Research Board, National Research Council, (1999))
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))
("NCHRP Synthesis of Highway Practice Report 35: Design and Control of Freeway Off-Ramp Terminals." Washington, D.C., Transportation Research Board, National Research Council, (1976))

6.13. Transit Facilities and Related Features [Future Edition]

Future editions of the HSM may include discussion of the safety effects of transit facilities for different road classes and environments. This discussion may include intermodal links, carpool lots, shared facilities, transit stop locations (with links to Chapters 3, 4, and 5), HOV lanes and dedicated bus lanes. The safety effect of providing park and ride and kiss and ride facilities may also be discussed here. Potential resources are listed in Exhibit 6-52.

Exhibit 6-52: Potential resources on the safety of transit facilities

DOCUMENT
(Farran, J. I., Korve, H. W., Levinson, H. S., and Mansel, D., "The Light Rail Transit Safety Experience." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 97-103.)
(Menta, V. K., Strate, H. E., and Saracena, A., "New Jersey Route 495 Exclusive Bus Lane Safety Study." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 319-325.)

6.14. Bicyclist and Pedestrian Facilities and Related Features [Future Edition]

Future editions of the HSM may include discussion of the safety effects of dedicated off-road pedestrian and bicyclist facilities, such as pedestrian over or under passes, shared-use paths, etc. Potential resources were not identified.

6.15. Toll Plazas [Future Edition]

Future editions of the HSM may provide information on the safety effect of various toll plaza designs and operational characteristics. Potential resources are listed in Exhibit 6-53.

Exhibit 6-53: Potential resources on the relationship between toll plazas and safety

DOCUMENT
(Menta, V. K., Strate, H. E., Boss, D. A., and Saracena, A., "Electronic Toll Collection and Safety at the Holland Tunnel." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 236-242.)
(Various, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Volume 1." FHWA-TS-82-232, Washington, D.C., Federal Highway Administration, (1982))

6.16. Weigh Stations [Future Edition]

To be addressed in future editions.

6.17. Special Events [Future Edition]

In future editions of the HSM, this section may provide information on the safety effect of special events that require closing roads or redirecting traffic, such as parades or festivals. Potential resources are listed in Exhibit 6-54.

Exhibit 6-54: Potential resources on the relationship between special events and safety

DOCUMENT
(Fitzpatrick, K., Balke, K., Harwood, D. W., and Anderson, I. B., "NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways." Washington, D.C., National Cooperative Highway Research Program, Transportation Research Board, (2000))

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Chapter 7: Road Networks

Chapter 7. Road Networks

CONTENTS

EXHIBITS

Chapters 3 to 6 provide information about the safety effects of specific treatments designed for road segments, intersections, interchanges and various other facilities. Chapter 7 considers how the safety of the road network as a whole is impacted by planning, design and operational decisions, and also by the road-use culture of the network's users.

National policy requires state and metropolitan authorities to develop long-range planning processes and to create long-range plans that will increase the safety of the transportation system for all users. This Chapter is concerned with the principles and philosophies that guide the processes and the policies that result.

How do long-range policy decisions impact safety at the network, corridor, and project levels? How do we ensure that we understand and maximize the safety benefits of our geometric and operational improvements in the wider context of population growth, land use issues, the transportation network and the human behavior of those who use the network, whether as motorized or non-motorized users? What is the best way to ensure that state and metropolitan authorities successfully incorporate safety into their long-range planning?

High-level policy and planning decisions affect the safety of the network at every level of the network. The decisions made affect the number of crashes expected to occur on the network by determining a whole range of issues, including, for example:

- How much travel takes place (how far people travel in the course of their daily activities);
- What mode of travel is used (whether people travel by train, subway, bus, car, bicycle or walking);
- What kind of facility is used (whether people travel on a freeway or an arterial);
- Whether road users pass through few high-volume intersections or many low-volume intersections;
- The distance between access points;
- The need for children to cross roads on their way to school; and
- The operating speeds implied by the local residential road network (e.g., straight wide roadways, crescents, or cul-de-sacs).

At the design and operational level of planning, some decisions (such as shoulder widening or the provision of a turn lane) have little effect on travel patterns over the network as a whole, but whenever a design or operational decision affects the network and the mode, route, or trip choice of users, the pattern of trips on the network and the safety effects on the network as a whole may change. One-way street systems, for example, illustrate how design and operational decisions may appear to focus on a relatively limited area, but have safety implications for the road network beyond the immediate site.

National policy expects transportation authorities to go beyond construction based strategies. Transportation authorities are expected to incorporate education and enforcement strategies into their goal for a safer transportation network. Although there is little detailed information on how driver and pedestrian behaviors vary and create a road-use culture or how that road-use culture evolves, it is clear that there are situations where the local road-use culture has an effect on safety. Examples include driver behavior where red-light cameras are installed, driver behavior at all-way stops, the attitude towards driving while impaired, the use of seatbelts, yielding to pedestrians, etc. In the case of both red-light cameras and all-way stops, there may be additional network safety effects. Drivers may anticipate the use of red-light cameras or all-way stops at other intersections and change their behavior accordingly.

7.1. Safety in Transportation Network Planning

Although a safe transportation system is desired and expected, safety has not been an explicit and pro-active part of the transportation planning process. Transportation planning has traditionally focused on capacity and congestion with some attention being given to operation and management. Safety has, however, become more prominent in the last decade.

The Transportation Equity Act for the 21st Century (TEA-21) in 1998 gave specific recognition to safety as a planning factor. For the first time, state agencies and Metropolitan Planning Organizations (MPOs) were required to incorporate safety (and security) criteria into their respective planning processes and activities in a comprehensive and multimodal way.

The Safe, Accountable, Flexible, Efficient Transportation Equity Act (SAFETEA-LU) became law in 2005. SAFETEA-LU has a strong focus on integrated, comprehensive safety planning and makes greatly increased funding available. The Act established the Highway Safety Improvement Program (HSIP) as a core program. The purpose of the HSIP is to reduce fatal and serious/life changing crashes. Strategic Highway Safety Plans (SHSP) are a new requirement (under the HSIP) and must be fully linked and integrated with the transportation planning process and associated plans. In addition, certain safety issues (work zones, older drivers, and pedestrians, including children walking to school) receive special emphasis in the Act. Flexibility is an important part of SAFETY-LU’s approach, allowing states to examine their own circumstances and to concentrate on their most critical safety needs.

Legislation has clearly established that safety must become a quantitative, permanent and key part of the long-range and short-range planning activities conducted by the various agencies involved in the transportation planning process at every level of the network. The safety needs of each level of the network from the local to state must be assessed and related to other levels of the network to create a seamless continuity of safety planning that is fully integrated with established planning procedures. The agencies involved include departments of transportation (DOTs), MPOs, transit agencies, local governments, and special district agencies. It is also necessary for planning agencies to relate to external agencies and organizations which have programs relating to safety planning. These include service organizations, commercial organizations and non-governmental organizations (NGOs). All of these relationships must be recognized and strengthened to accommodate the consideration of safety issues.

The many agencies involved need to adopt a common safety vision with safety goals and objectives that are not only explicit and pro-active, but also quantifiable and quantified. It is the creation of clearly quantified goals and objectives that leads to a common commitment to track and achieve those goals and objectives. NCHRP Report 501, by Bahar et al., provides additional guidance to integrate all stakeholders in a systematic and proactive process (*2*).

State DOTs are responsible for establishing long-range goals and objectives for their transportation systems. MPOs develop long-range goals and objectives for the metropolitan areas.

As the introduction of explicit safety in transportation planning (safety conscious planning) is relatively new, (*3*) there is little quantitative information on its accident reduction impact and potential. Safety conscious planning is discussed in Section 7.2.2.

Exhibit 7-1: Resources examined to investigate the safety effects of incorporating safety into the transportation planning process

DOCUMENT	DESCRIPTION	COMMENT
(*1*) Washington, S., Meyer, M., van Schalkwyk, I., Dumbaugh, E., Mitra, S., and Zoll, M., "Incorporating Safety into Long-Range Transportation Planning." NCHRP Report 546, Washington, D.C., National Cooperative Highway Research Program, (2006)	The final report was reviewed when it was published in 2006.	Added to synthesis. Little or no quantitative information.
(Washington, S., Meyer, M., van Schalkwyk, I., Dumbaugh, E., Mitra, S., and Zoll, M., "Draft Guidance: Incorporating Safety into Long Range Transportation Planning." NCHRP 8-44, Washington, D.C., National Cooperative Highway Research Program, (2004) pp. 1-65, plus Appendix, Exhibits.)	The draft report is a guidebook that provides overall direction on how safety is integrated into the transportation planning process.	Superseded by NCHRP Report 542
(*4*) Lamptey, G., Labi, S., and Sinha, K. C., "Investigating the Sensitivity of Optimal Network Safety Needs to Key Safety Management Inputs." No. TRB 2005 Annual Meeting CD-ROM, Washington, DC, Transportation Research Board, (2005) pp. 1-21.	The paper combines engineering principles with economic evaluation to assess the long-term safety needs of a network and the optimal level of funding required to address the safety needs.	Added to synthesis. Little or no quantitative information.
(*2*) (Bahar, G., Masliah, M., Mollett, C., and Persaud, B., "NCHRP Report 501: Integrated Safety Management Process." Washington, D.C., Transportation Research Board, National Research Council, (2003))	Development of an Integrated Safety Management Process.	Added to synthesis. Little or no quantitative information.
(Petzold, R., "Proactive Approach to Safety Planning." Public Roads, Vol. 66, No. 6, McLean, Va., Federal Highway Administration, (2003) pp. 1-8.)	The paper discusses safety-conscious planning and the value of taking a proactive approach to improve safety.	Added to Section 7.2. Little or no quantitative information.
(*5*) (Lord, D. and Persaud, B. N., "Estimating the safety performance of urban road transportation networks." Accident Analysis and Prevention, Vol. 36, New York, N.Y., Elsevier Ltd., (2003) pp. 609-620.)	The paper describes the application of models designed to prevent unsafe situations from arising by allowing planners to estimate the number of crashes on digital or coded urban transportation networks.	Added to synthesis. Little or no quantitative information.
(U.S.Department of Transportation, "Considering Safety in the Transportation Planning Process." Washington, D.C., U.S. Department of Transportation, (2002))	The report's focus is on incorporating safety into the transportation planning process for the multimodal transportation system and on providing planners with information and techniques to better understand the role of safety within this process.	Not added to synthesis. Little or no quantitative information.
(Litman, T., "Traffic Calming: Benefits, Costs and Equity Impacts." Victoria Transport Policy Institute, (1999)	This paper describes a framework for evaluating traffic calming programs.	Added to Section 7.4. Little or no quantitative information.
(Tarko, A. P., Sinha, K. C., and Farooq, O., "Methodology for Identifying Highway Safety Problem Areas." Statistical Methods and Accident Analysis for Highway and Traffic Safety, Transportation Research Record 1542, Washington, DC, Transportation Research Board, (1996) pp. 49-53.)	The paper develops a methodology that can be used to identify locations and areas that need safety treatment.	Not added to synthesis. Little or no quantitative information.

7.1.1. Incorporating Safety into the Transportation Planning Process

Integrating safety into transportation planning affects every aspect of the transportation planning process. To reduce the number of accidents and their severity, and to increase the safety of the road network through an integrated and pro-active approach, it is necessary to consider safety at every stage of the planning process. Safety must be part of the planning, implementation and evaluation of the transportation network.

NCHRP Report 546, by Washington et al., describes current thinking and progress towards a transportation process that fully recognizes and integrates safety(*1*). They point out that it is important that the evaluation of safety implications takes place during the first steps of the transportation planning process, not when the process is already well established(*1*). Washington et al. propose using key planning steps to integrate safety into the entire transportation planning process(*1*).

The objective of Washington et al.'s research "was to develop a guidance manual for practitioners that identifies and evaluates alternative ways to more effectively incorporate and integrate safety considerations in long-range statewide and metropolitan transportation planning and decision-making processes ((*1*), pg iv). The authors envisage a seven step process for incorporating safety considerations into transportation planning in a comprehensive manner(*1*). "Safety" is defined to "include all externalities of the transportation system that result in personal harm—including both physical and emotional—such as minor and severe injuries and fatalities, and for all system users such as pedestrians, bicyclists, transit riders, motorists, and commercial vehicle operators" ((*1*), pg vii).

The creation of the vision and the identification of strategies that can increase the safety of the road network first require an understanding of the nature of the safety problems faced. This understanding needs to include both the "big picture" and the specific issues facing a particular regional or local area. Examples of specific issues include run-off-the road crashes in rural areas, pedestrians and bicyclists in some urban areas, and the elderly in retirement communities. The nature of the problem will affect the vision and the type of strategies adopted to integrate safety into the transportation planning process.

The vision is the start of the process. Whether the vision is a broad statement of the desired end-state or a well-defined scenario, it provides the foundation for incorporating safety into the goal and objectives. The goal and objectives then provide a basis for identifying system performance measures, a "relatively new concept in transportation planning" ((*1*), pg 22), and the data needed to evaluate progress towards the goal and objectives.

It is likely that as safety becomes better integrated into the transportation planning process, safety will have a greater influence on strategies and projects. As the quality of data and the sophistication of analysis improve, it will eventually be possible to create models that estimate the safety of the network. This will enable planners to make quantitative comparisons of strategies.

7.1.2. Seven Key Steps for Incorporating Safety into the Transportation Planning Process

Washington et al. discuss seven key steps that are required to incorporate safety into the transportation planning process (*1*). These steps are:

Step 1: Incorporate Safety into the Vision Statement

Step 2: Incorporate Safety into the Set of Goals and Objectives

Step 3: Incorporate Safety into System Performance Measures

Step 4: Incorporate Safety into Technical Analysis

Step 5: Evaluate Alternative Projects and Strategies

Step 6: Develop Plan and Program

Step 7: Monitor System Performance

7.1.2.1. Step 1: Incorporate safety into the vision statement

The process of planning a safe network needs a vision that is made clear and realistic. The definition of goals and objectives will "serve to direct subsequent planning activities for assessing the relative contribution of different alternatives or strategies in achieving desired outcomes" ((*1*), pg 21). Safety professionals and advocates should be involved from the outset.

The vision statement refers to the desired characteristics of future travel experiences. Washington et al. give the example of Oakland, California's vision statement: "The highest aim of the Metropolitan Transportation Commission is to plan for, deliver and manage a safe, efficient, integrated multimodal transportation system for the San Francisco Bay Area".((*1*), pg 28). Although very broad, this statement includes safety and is probably the result of an extensive consultation process that brings safety issues to the attention of many agencies and the public. The vision statement provides a reference for all future debate and decisions.

7.1.2.2. Step 2: Incorporate safety into the set of goals and objectives

The goals and objectives should explicitly address the main safety issues facing the region, including those relevant to non-motorized users. The goals and objectives should be developed with an integrated approach including the enforcement, education and emergency aspects needed to support the safety initiatives. With safety clearly built into the planners' goals and objectives, safety can play an important role in comparing and evaluating different transportation projects.

Goals have traditionally been general, but it is now recognized that goals should be measurable, and that any targets specified (such as a 20% reduction in fatal accidents) should be realistic and achievable.

Examples of traditional safety goals include:

- Increase highway safety; and
- Provide for a safe and effective circulation system that minimally impacts the area's open space, and scenic roadways.

AASHTO's Strategic Highway Safety Plan provides a good example of an explicit and quantifiable goal: "To reduce the number of fatalities from traffic crashes by 5,000 to 7,000 lives annually" (*2*). A quantifiable goal will enable the small contributions of each one of the identified objectives and strategies toward achieving this goal to be noted.

Objectives are more precise and measurable than goals can be. Examples of safety objectives include:

- Reduce fatal run off the road accidents in the region by 10 percent over the next three years;
- Reduce drug and alcohol related accidents by 25 percent within 5 years; and
- Reduce pedestrian and bicycle related injuries and fatalities by 50 percent.

7.1.2.3. Step 3: Incorporate safety into system performance measures

Safety performance measures should be designed to ensure that the planning process and its results are accountable. "Performance measures are used to monitor the characteristics of transportation system performance and to determine the extent to which desired goals and objectives are being achieved" ((*1*), pg 32). Performance measures can provide quantitative information on the safety impact of land use and transportation network planning decisions and useful information that can be used to refine the action plans should this become necessary, or alternatively modify the originally set goals and objectives. As data become available, it should be possible to "develop a state or regional strategy for monitoring the safety of the multimodal transportation system" to identify problem areas pro-actively ((*1*), pg 60). This monitoring strategy will include safety information that will raise the priority of safety-beneficial projects and increase the likelihood of such projects being incorporated into the network.

"Evaluation of system performance has traditionally relied on measures of congestion, travel delay, traffic volumes, and measurements of the condition of such things as pavements and bridges" rather than specific safety measures ((*1*), pg 32). To be successful, the safety performance measures must be valid indicators of safety based on good data and analysis. These examples are from the Minnesota Statewide Transportation Plan:

- Number of accidents per vehicle-mile traveled;
- Number of accidents between cars and trains at railroad crossings; and
- Total number of roadway fatalities ((*1*), pg 33).

Other examples might include "normalized accident rate performance measures (e.g., fatal crashes per million vehicle miles of travel), unit costs and cost-effectiveness measures (e.g., dollars invested in countermeasure), alcohol and drug involved crashes (e.g., number of intoxicated young drivers) and some other measures (e.g., restraint usage rates)" ((*1*), pg 34).

Safety performance measures should be included in the evaluation criteria used to compare projects and strategies. Washington et al. suggest discussing the safety-related performance measures with transportation modelers "to determine if the measures can be predicted in future years" and used to forecast the safety performance measures of alternative approaches and scenarios ((*1*), pg 34). Planners should prepare "Prepare a set of prototypical safety-related performance measures that reflect the goals and objectives [that have been adopted for the planning effort]. This set should be limited in number to only those measures that provide critical information on the safety performance of the transportation system and that could presumably be affected by the types of strategies that will result from the planning process" ((*1*), pg 34).

Washington et al. provide an example of the use of safety performance measures in Minnesota where trend-based projections were used to show that the number of road fatalities was likely to rise from 604 per year to 735 per year. The introduction of moderate enforcement measures was expected to reduce the number of fatalities to 550. Similarly, Bahar et al. provide detailed descriptions of examples of the application of performance measures (*2*).

7.1.2.4. Step 4: Incorporate safety into technical analysis

Technical analysis uses safety data and appropriate models and tools to identify problems within the system and to assess the strategies available for addressing the problems. Comprehensive, timely and high quality data are essential, but may not always be available. Washington et al. refer to the importance of quality data through their report.(*1*) New data collection methods, including GIS, may ease some of the problems. Bahar et al describe best practice suggestions for databases (Appendix B2) (*2*).

Many safety analysis tools are becoming available. The choice will depend on data availability, the scale of the analysis (local, corridor, regional), amount of prediction required, the degree of uncertainty, the time available, the number of modes included in the analysis, and so on. Washington et al. list the tools available in their Appendix C and summarize the purpose, level of detail and amount of expertise needed for each one(*1*). Similarly, Bahar et al. provide an appendix with examples of the application of various tools for the incorporation and evaluation of safety after the implementation of selected strategies (*2*).

As Washington et al. point out, “project and corridor-level safety tools have been available for some time and are used in many safety studies”, but safety prediction models and “regional level planning tools …. are not as readily available” ((*1*), pg 43). Methods and tools are required to predict long-range safety performance and enable planners to be proactive in formulating solutions to safety problems.

Washington et al. describe the work currently taking place to develop PLANSAFE as an accident forecasting tool in Arizona ((*1*), pg 129). PLANSAFE uses population growth and various “built” scenarios to forecast the expected number of fatal, injury, pedestrian and total crashes over ten years in small traffic analysis zones (TAZ) and neighborhoods (collections of TAZ). Washington et al. provide an interesting list of the factors incorporated into PLANSAFE to capture “most of the major factors involved with crashes at the TAZ level” ((*1*), pg 149). The factors include weather (proportion of wet/icy/snow/foggy/sunny days per year), the proportion of various high risk driving populations (young, elderly, unemployed, DUI records), issues affecting high-risk non-motorized populations (number of crosswalks, number of school, sidewalk mileage, bicycle facilities), facilities’ speed, design and access control (proportions of local/collector/arterial/rural highway/interstate mileage), and the number of potential conflicts on the network (signalized/unsignalized intersections, intersection density, total area). The model offers predictions to show when and where an outcome occurs.

As accident forecasting models are further developed, it should be possible to compare and predict the safety impact of major long-range transportation planning decisions that influence the safety of the transportation system. Major strategies include:

- Reducing travel exposure by using land use arrangement and density to reduce the need to travel and the distance traveled in the course of their daily activities;
- Encouraging travelers to use the safest modes; and
- Encouraging travelers to use the most appropriate and safest facility for each trip so that travelers’ exposure to conflicts is reduced during their journeys.

It should also be possible to provide quantitative assessments of the way in which changes on one part of the network may lead to safety impacts elsewhere on the network so that these impacts can be evaluated and the trade offs analyzed.

Few studies have as yet successfully tackled network wide safety analysis. An exception is the work of Lord and Persaud. In 2004, Lord and Persaud published research into developing a tool that would help to prevent unsafe situations from arising by allowing planners to estimate the number of crashes on digital or coded urban transportation networks (*5*). Like PLANSAFE, Lord and Persaud’s approach offers simple accident predictions rather than explanations of accident occurrence. Their paper provides many insights into the problems involved in modeling and predicting accidents at the network level.

Lord and Persaud conducted a literature review, but found very few publications on the application of safety performance functions (SPFs) to transportation networks. The research available had limitations. For example, models were often not calibrated or validated for the networks studied. Lord and Persaud focused on the macroscopic representation of physical networks and the application of SPFs (*5*).

Lord and Persaud used Toronto, Canada data from 1990 to 1995 to develop SPFs for nodes and links (mid-block and at minor intersections). The researchers pointed out that several years of data are needed to take into account year to year accident variations due to economic conditions, weather, reporting practices, etc. Their models are for all accident severities combined. The models were applied to two sample networks (*5*):

- A small street system in Toronto (six links, six nodes, one centroid); and
- A hypothetical network, 4 km wide by 2 km long (18 links, 15 nodes, 6 centroids, with 9,800 vehicle-trips assigned to the network).

The network representations were macroscopic, excluding local (residential) roads and layouts (which were considered to be microscopic networks). As Toronto is laid out on a grid, the study did not cover a radial layout or curving roads.

Lord and Persaud concluded that ((*5*) pg 615):

- The models predicted values similar to true accident counts; and
- Traffic flow explained over 50% of crash occurrences.

Lord and Persaud aimed to estimate the safety of different scenarios even before the detailed characteristics of the physical network were known. They concluded that it is feasible to estimate the safety of transportation networks at the planning stage, that SPFs can be used to estimate crashes on digital transportation networks and that the models used in their study provide a good start (*5*). Traffic flow was by far the most important variable. With further refinement of Lord and Persaud's approach, planners could use the tool to plan site specific measures and redistribute traffic on network, and optimize the occurrence of accidents on critically affected links and nodes.

Lord and Persaud also list some important issues and problems that arise in attempting to predict the safety of a network (*5*):

1. Prediction of traffic flows – transportation planning software may give inaccurate traffic flows and lead to inaccurate appraisal of network safety.
2. Applicability and accuracy of SPFs – The SPFs used in the study were developed for Toronto and would have to be recalibrated for other jurisdictions.
3. How the network is coded – The relationship between segment length and accident counts is non-linear. Where links are sub-divided into many segments, the model must be adjusted to avoid over-estimation of accidents on links.
4. Road changes – The modification of a road characteristic is likely to affect the road's safety. For example, when a road is widened, there may be changes in land use along the road and these may lead to additional minor intersections and driveways, but the models are unlikely to capture these changes. Lord and Persaud feel that it is possible to develop more detailed models, but it is difficult to obtain readily available and reliable information about the physical characteristics of the network. This is a serious constraint. As it is difficult to know the land use and physical characteristics of roads and intersections at the planning stage, it is difficult to apply detailed models. Lord and Persaud also point out that their models may not apply in the long term as factors that influence crashes (economic conditions, new laws, bye laws, etc) change over time.

5. Networks that are not yet built – Lord and Persaud's models need data on minor intersections and links, but it may not be possible to know the exact location of minor intersections and links on networks that are not yet built. A general purpose model is needed.
6. Software – The models were calculated on spreadsheets as they could not be used within existing transportation planning software. The computation requirements were very cumbersome. There is a need to develop transportation planning software that can accommodate accident prediction.

Washington et al. outline similar limitations on safety forecasting models ((*1*), pg 147).

Lord and Persaud provide a list of avenues for further research (*5*):

- Additional models for nodes (by crash type, time periods);
- Estimation of safety in the zones not included in the models (i.e. local streets) to be used to predict total crashes for the study area;
- Simplification of computation of crashes on links (Lord and Persaud used a series of three models);
- Incorporation of finalized SPFs into transportation planning software;
- Investigation of how the use of AMFs to estimate minor changes in the network fits into safety research at the network level; and
- Investigation of network-based predictive models that consider the network as one entity.

The realization of those studies will enable planners to predict safety more explicitly and more accurately than is possible at present.

7.1.2.5. Step 5: Evaluate alternative projects and strategies

Evaluation comprises the process of comparing different courses of action and selecting the most beneficial. The process must be readily accessible both to decision makers and to the public.

A suitable evaluation methodology is necessary to make valid evaluations of alternative projects and strategies. Most safety evaluations are based on listing and ranking the evaluation criteria, or assigning scores or weights, or conducting a cost-benefit analysis. The evaluation criteria should be specified early in the planning process so the necessary data and tools can be made available. The performance measures defined in Step 3 are integrated into the evaluation and selection of alternatives.

Whether the evaluation is based on simple ratings or on far more complex procedures, it must be fair, open, and based on reasonable assumptions regarding, for example, estimates of accident costs. It must also be sensitive enough to analyze trade offs and to draw worthwhile distinctions between options.

It is important that the adopted goals and objectives be compared against the expected outcome of the alternative projects and strategies, as these are some of the activities contributing toward the goal or objectives. Bahar et al. provide a description of methodologies for the determination of level of implementation and success in meeting the goal and objectives (Appendix D3 of (*2*)).

Lamptey et al. (*4*)have recently developed an approach that agencies can use to assess the long-term safety needs of a network using a comprehensive and system wide methodology . "The paper addresses the issue of optimal funding amounts to address the safety needs for physical highway infrastructure for a state highway network" ((*4*) pg 18). The study used data from Indiana's state highway network.

Lamptey et al.'s approach combines engineering principles with economic evaluation and business practices. The study finds that the projects proposed for the state of Indiana "on the average, a total of 107 crashes (36 fatal/injury and 71 PDO) are expected to be saved for every $1 million increase in average safety expenditure" ((*4*) pg 15).

The researchers investigate the impact of different levels of funding on network safety. They note that the definition of safety needs varies with the method used to identify locations requiring safety measures and the economic evaluation criteria used. They also note that the benefits of safety improvement projects are non-linear: crash reductions per dollar spent decline after a certain point. Lamptey et al. suggest that their approach can be used to determine the optimal level of funding and to compare that level of funding with current expenditure. They estimate that the optimal funding on the physical infrastructure of the Indiana state highway system they examined would imply "an average annual amount of $450 per mile from 2005 to 2015."

7.1.2.6. Step 6: Develop plan and program

The way in which safety projects are selected, prioritized and incorporated within transportation plans will critically affect how successfully safety is integrated into the transportation planning process(*1*). The plans must include clearly identified safety projects. These projects must be consistent with the goals, objectives and performance measures of any other safety plans that may be introduced in the area.

There are many possible approaches. Washington et al. found that MPOs tend to include general traffic management and pedestrian and bicyclist safety in their transportation plans. DOTs tend to include general traffic management, pedestrian and bicyclist safety, and intermodal crossings. Washington et al. offer a far wider range of safety issues that should be included ((*1*), pg 54). Examples include:

- Targeting specific groups for education efforts (elderly drivers, transit, work zones, etc);
- Enhancing traffic enforcement (safety audits, traffic management, etc);
- Improving data collection and management; and
- Maximizing personal vehicle safety (seat belts, aggressive driving, weather issues, DUI, etc.).

Many states have developed detailed strategies and actions for their safety plans.

The choice of projects for transportation improvement programs will depend on negotiations with stakeholders and also on prioritization procedures. When safety issues are explicitly recognized and safety effects are quantified, the priority given to safety projects in the selection process will increase.

7.1.2.7. Step 7: Monitor system performance

It is essential to establish whether safety goals are being achieved. The safety performance of the transportation plan must be monitored using good quality data and an effective safety management system to highlight the successes and to facilitate changes to strategies. The feedback should be used to refine the plan's goals, objectives, performance measures, problem identification, project analysis and evaluation. {Washington, 2006 3469 /id}

Bahar et al. describe nine methodologies for the monitoring of the outcomes of implementation of selected strategies (Appendix D1 (*2*)).

7.1.3. Summary

The integration of safety into transportation network planning continues to make progress towards the goal of inherently safe road networks. Milestones and important developments include recent legislation (TEA-21 in 1998 and SAFETEA-LU in 2005), and the on-going development of quantitative models and other tools that can be used to provide a quantitative assessment of the impact of safety projects and safety planning on the road network.

7.2. Safety in the Planning and Design of Residential Neighborhoods and Commercial Areas

This section discusses the safety issues involved in planning and designing residential neighborhoods and commercial areas. The safety planning of residential neighborhoods and commercial areas provide two good examples of the safety issues faced by those involved in the design of road networks at local levels of the road network. The explicit consideration of safety (in terms of the expected frequency and severity (and type) of accidents) during the planning and design stages (as discussed in Section 7.1) creates a proactive opportunity for all highway professionals to construct roadways that minimize the need for safety mitigation after construction is complete.

Two important approaches are available for ensuring safety is considered explicitly and proactively:

- Self-explaining roads; and
- Safety conscious planning.

Section 7.2.1 discusses self-explaining roads, which are especially relevant to the local level of planning. Section 7.2.2 discusses safety conscious planning in general. The principles are then related to residential neighborhoods and commercial areas (Section 0).

Exhibit 7-2: Resources examined to investigate safety in the planning and design of residential neighborhoods and commercial areas

DOCUMENT	DESCRIPTION	COMMENT
(*10*) (Arizona Department of Transportation, "Safety Conscious Planning: A New Concept." Phoenix, Ariz., Arizona Safety Conscious Planning Forum, (2002) pp. 1-14.)	The report summarizes the discussions of 40 experienced professionals regarding safety-planning for TEA-21.	Added to synthesis. Little or no quantitative information.
(Davis, G. A., Sanderson, K, and Davuluri, S., "Development and Testing of a Vehicle/Pedestrian Collision Model for Neighborhood Traffic Control." MN/RC - 2002-23, St. Paul, Minn., Minnesota Department of Transportation, (2002))	The study assessed the effect of vehicle traffic volumes and speeds on pedestrian safety in 25 residential streets.	Not added to synthesis.
(*12*) (Roberts, K., "Safety Conscious Planning - The Development of the Safer Transportation Network Planning Process." (2001))	The report addresses Safety Conscious Planning initiatives for developing inherently safe transportation networks.	Added to synthesis. Little or no quantitative information.
(*13*) (Depue, L., "Safety-Conscious Planning." E-C025, TRB Committee on Traffic Safety Management, (2001))	The report briefly discusses Safety Conscious Planning mainly in terms of administrative issues.	Added to synthesis. Limited qualitative information.

DOCUMENT	DESCRIPTION	COMMENT
(*14*) (Herrstedt, L., "A Vision for the Future - Safe Infrastructure." European Union, (2001))	The paper briefly examines self-explaining roads and forgiving roads in a European context.	Added to synthesis. Little or no quantitative information.
(*15*) (Bonneson, J. A., Parham, A. H., and Zimmerman, K., "Comprehensive Engineering Approach to Achieving Safe Neighborhoods." SWUTC/00/167707-1, College Station, Tex., Texas Transportation Institute, (2000))	The research investigated the problem of drivers diverting from busy arterials through residential areas where they create safety problems.	Added to synthesis. Little or no quantitative information.
(*16*) (Dijkstra, A., "Transforming 'Traditional' Urban Main Roads into Sustainably-Safe Roads." Washington, D.C., TRB, (2000))	The paper outlines Dutch recommendations for traffic in built-up areas and the principle of sustainable safe traffic.	Added to synthesis. Little or no quantitative information.
(*17*) (van Vliet, P. and Schermers, G., "Sustainable Safety: A New Approach for Road Safety in the Netherlands." Rotterdam, The Netherlands, Ministry of Transport, Public Works and Water Management, (2000))	The report discusses the history and principles of sustainable safety in Holland.	Added to synthesis. Little or no quantitative information.
(*18*) (Institute of Transportation Engineers, "The Traffic Safety Toolbox: A Primer on Traffic Safety." Washington, D.C., ITE, (1999))	The report is a convenient primer that provides readers with the safety personal knowledge and expertise of many authors.	Added to synthesis. Little or no quantitative information.
(West, J. and Lowe, A., "Integration of Transportation and Land Use Planning through Residential Street Design." ITE Journal, Vol. August, (1997) pp. 48-51.)	The paper examined overburdened residential street in Eugene, Oregon with the emphasis on the rigidity of development codes.	Not added to synthesis. No quantitative information.
(*19*) (Giese, J. L., Davis, G. A., and Sykes, R. D., "The Relationship Between Residential Street Design and Pedestrian Safety." Boston, Mass., Institute of Transportation Engineers, (1997))	The study investigated whether physical and/or perceptual elements of residential streets affect vehicle speeds.	Added to synthesis. Little or no quantitative information.
(*22*) (Hunter, W. W., Stutts, J. S., Pein, W. E., and Cox, C. L., "Pedestrian and Bicycle Crash Types of the Early 1990's." *FHWA-RD-95-163*, McLean, Va., Federal Highway Administration, (1995))	Review of pedestrian and bicycle crashes.	Added to synthesis. Little or no quantitative information.
(Wegman, F., "Safety Effects of Road Design in Europe." D-96-14, (1996))	The report discuses road design standards and traffic regulations in Europe.	Not added to synthesis. No quantitative information.
(*20*) (Theeuwes, J., "Self-explaining roads: An exploratory study." (1994))	The study investigated improvements for self-explaining roads based on the driver's visual search process while driving.	Added to synthesis. Little or no quantitative information.

The design and safety of residential neighborhoods require special consideration due to the presence of particularly vulnerable road users: pedestrians, children, the elderly, and bicyclists. In the past, most residential areas were relatively safe, and residential streets carried local traffic and low traffic volumes. With increasing traffic volumes, parks and community centers provided a safe alternative for children's playing and for local social activities. As traffic continued to increase, walking or cycling to parks and community centers became challenging and required special facilities for non-motorized and vulnerable users.

Fewer people nowadays rely on small local amenities (such as stores, schools or workplaces) to which they can safely walk. Schools that served the immediate community have been replaced by large schools with wide catchment areas. Many residential streets are wide and over designed for their desired function and role in modern shared-space residential neighborhoods. Residential streets can often accommodate large local and non-local volumes of traffic moving at high speeds. Higher volumes and operating speeds have led many communities to demand greater safety in their residential areas. Communities want lower traffic volumes and lower operating speeds.

In business and retail commercial areas, concern about decreasing safety on arterials and collectors has demanded attention and the introduction of traffic management measures that will sustain the vitality of the businesses. Small local shopping areas have been replaced by larger stores which are often accessible only by car and which raise the question of the safety of location and internal design of commercial areas.

One-way and turn restrictions (Section 7.3), traffic calming measures (Section 7.4), and access management policy (Section 7.5) provide some mitigation and "fix" measures to help achieve safer environments for all road users within existing residential and commercial areas.

The evidence presently available regarding the best choice of urban layout and some types of road design is mostly qualitative, anecdotal and sometimes somewhat based on personal philosophy. Very limited quantitative information was found. Research is required to quantify the safety impact of medium and local level planning decisions on a wide variety of network settings, road types, and traffic volumes.

7.2.1. Self-Explaining Roads

The concept of self-explaining roads was introduced in Holland in the 1990s. Highway professionals sought ways to promote a self-enforcing and harmonious environment for all road users. Self-explaining roads use design and appearance to provide consistent and correct information about the function and role of the road, encouraging drivers (and other road users) to adjust their speed and behavior in response to the adjacent land use and environment.

"The aim should be to create a simple and unambiguous, clear and understandable, readable and recognizable traffic situation – easy to handle for the road users – without too many distracters and information overload – and leaving no doubt about the reasonable speed level, the give-way situation, location and movement of other road users around. The aim is simplicity and clearness instead of complexity and ambiguity!" (*14*)

Self-explaining roads are intended to reduce driver errors and crashes by ensuring that safety is built into the road environment. The design of the road environment is adapted to meet the limitations of human information processing and to match driver expectations and experience. From their experience of various road environments, road users develop "prototypical representations of different road environments" ((*20*), pg 5). A self-explaining road is designed to meet these expectations. Freeways, for example, provide a clear and immediate mental image of the type of driving and driving speed to be expected. Giese et al., in their study of the relationships between street elements and vehicle speeds, investigated whether the physical and/or perceptual elements of residential streets were important (*19*). Giese et al.'s recommendations include "shorter" street lengths for new residential developments (length not specified) and designs that create a sense of spatial enclosure as this appears to be associated with slower speeds on residential streets.

In a residential setting, the design of a self-explaining road may include familiar traffic calming techniques and various other measures, such as influencing driver behavior by changing the road surface (e.g., using colored road surfaces to distinguish bicycle lanes), introducing narrow street patterns, and removing visually intrusive signs.

7.2.1.1. Classification of self-explaining roads

The move towards ensuring that roadways are "self-explaining" requires roads to be appropriately classified. Some roadways may have to be reclassified and redesigned to conform to the self-explaining approach. Each level of classification must be designed to match the desired operating speed of the road. In the Netherlands, van Vliet and Schermers distinguished three categories of roads important to sustainable safety and self-explaining roads (*17*):

- Roads with a through function (for the rapid movement of through traffic);
- Roads with a distributor function (for the distribution and collection of traffic to and from different districts and residential areas); and
- Roads with an access function (providing access to homes and shops while ensuring the safety of the street as a meeting place. Roads with an access function are residential streets.).

Each road category requires careful design that matches its function and complies with the following three safety principles (*17*):

- Functionality (preventing unintended use of the infrastructure);
- Homogeneity (preventing major variations in the speed, direction, and mass of vehicles at moderate and high driving speeds); and
- Predictability (preventing uncertainty among road users).

The van Vliet and Schermers report emphasizes the distinction between roads with a through function and roads with an access function, "roads with an access function should not offer time-saving connections to through traffic (that is: traffic traveling to or from a location outside the immediate area); and roads with a through function should not offer direct access to homes, schools, offices, factories, sports facilities, etc." (*17*).

Bonneson et al. investigated safety in residential neighborhoods, especially the problem of poor differentiation of streets according to traffic function (*15*). Bonneson et al. were concerned about motorists diverting from slow, crowded arterials to the residential street system where they add to neighborhood traffic volumes and increase crash exposure for pedestrians, bicyclists, and other vehicles. The researchers focused on various "fix" treatments implemented to achieve a more self-explaining road network including neighborhood traffic management techniques (street closures, speed humps, traffic circles, and roadway narrowing) and corridor traffic management techniques to increase arterial travel speed (signalization improvements, geometric improvements, and access management). Bonneson et al. noted that the traffic management techniques reduced both traffic volumes and crash rates (*15*).

7.2.1.2. Self-explaining roads in residential areas

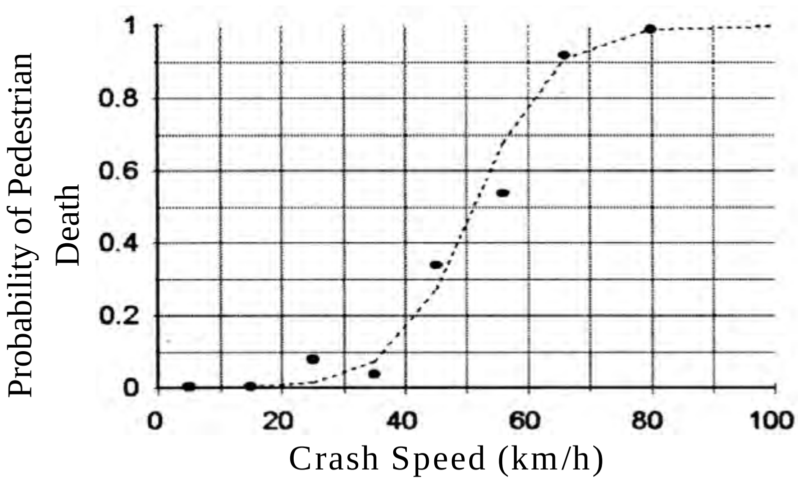
The design of self-explaining roads gives drivers a clear view of other road users. Drivers using self-explaining roads in residential areas expect to encounter children, pedestrians and bicyclists from the "look" of the road and its surroundings. According to the NHTSA report "Traffic Safety Facts 2000", fatal pedestrian crashes are most commonly due to improper crossing of the roadway or intersection (30%), followed by walking or playing in the roadway (*21*). Hunter et al. found that the main human factor problems contributing to pedestrian crashes included the limited time that drivers have to respond to unanticipated pedestrian movements, blocked vision, inadequate searching and checking by pedestrians and drivers (especially on left turns), speeding, and pedestrians assuming that they are far more visible than they actually are (*22*).

(Additional information about pedestrian safety is available in Section 3.3 Pedestrian and Bicyclist Safety on Roadway Segments, Section 4.3 Pedestrian and Bicyclist Safety at Intersections, and Section 5.3 Pedestrian and Bicyclist Safety at Interchanges. Future editions of the HSM may also include additional discussion about bicyclist and pedestrian facilities in Chapter 6.)

In 1984, Holland decided that "residential areas should be transformed into zones with a speed limit of 30 km/h"(*16*). Residential areas are designated as 18 mph (30 km/h) zones and have been found to be "relatively safe … despite considerable variation in the directions and mass of vehicles using them. Their safety [is] attributable to driving speeds and small speed differences between different road users" (*17*), pg 10). The Dutch have continued to work towards implementing appropriate measures in residential areas to support the 18 mph (30 km/h) zoning. From 1998 to 2001, there was a plan to add "at least 12,000 kilometers of infrastructurally adapted 30 km/h roads" (*17*), pg 14).

The lower vehicular speeds along self-explaining roads are particularly important for pedestrian safety and reduce the difficulties of pedestrians who are seeking appropriate crossing gaps in traffic. Pedestrians are especially at risk as vehicle speeds increase. Exhibit 7-3 shows how the relationship between speed and the probability of a pedestrian fatality rises rapidly when the crash speed exceeds about 18 mph (30 km/h) (*23*).

Exhibit 7-3: The relationship between speed and the probability of pedestrian fatality (23)



Children are highly vulnerable to speeding traffic. Research suggests that children do not have the maturity needed to cross the street safely until they are 9 to 12 years old (Sandels, 1966 as cited in (*24*)). Children are often impulsive and unpredictable with short attention spans and little understanding of danger. They may dart into traffic without thinking. Children lack the experience necessary to judge speed, vehicle approach time, and gaps in the traffic.

The Dutch have selected four demonstration projects to determine the effects of the concept of self explaining roads and sustainable safety. van Vliet and Schermers also mention 13 pilot areas where the creation of 18 mph (30 km/h) self explaining roads improved safety and the quality of life. In these pilot areas, a study found that (*17*), pg 20):

- The number of movements by motor vehicles fell by 20 to 30%;
- The number of accident casualties declined by 30% on average; and
- 80% of local residents were satisfied with the creation of an 18 mph (30 km/h) zone.

It is clear from the Dutch experience that detailed knowledge about driver perception of residential road environments can be used to influence driver behavior through changes in road design and traffic control strategies. The design of a self-explaining road can elicit safe behavior by encouraging and persuading drivers to reduce speed voluntarily and more or less automatically in response to the design itself.

There is some evidence of increased safety after the implementation of the self-explaining roads, but there are no AMFs at this time.

7.2.2. Safety Conscious Planning

Safety Conscious Planning (SCP) is a comprehensive, system wide and proactive process that integrates safety into transportation decision making for all transportation modes including walking, cycling, and transit. SCP aims to create safety planning procedures that are explicit and quantifiable. SCP is not limited to consideration of specific sites or “black spots”, but includes corridors and the entire transportation network at the local, regional, and state levels, as discussed in Section 7.1. SCP is also not limited to current safety problems, but aims to reduce the number of accidents by establishing inherently safe transportation networks by identifying opportunities to prevent future hazards and problem behaviors. On an inherently safe transportation network, it is difficult for the driver to have a crash. Road safety improvements are achieved through small changes, targeted at the whole network (*13*)

As discussed in Section 7.1, statewide and metropolitan planning agencies must consider the strategies and projects and that will increase the safety of the transportation network for motorized and non-motorized users. SCP assists transportation planners to consider safety more effectively, both in the long- and short-term transportation planning process.

“The short-term objective is to integrate safety considerations into the transportation planning process at all levels, specifically the Strategic Highway Safety Plans (SHSP), Statewide Transportation Improvement Programs (STIP) and the Transportation Improvement Programs (TIP) developed by the State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) respectively. This step should be followed by consideration of safety objectives in the longer range, 20 year plans that the state DOTs and MPOs are required to prepare and update periodically.(*13*)

Safety conscious planning is, by definition, comprehensive, network wide and multimodal. Almost every aspect of safety planning for residential and commercial areas can be considered in safety conscious planning terms.

Since safety conscious planning is a relatively new concept, definitive guidelines are not yet available and clear strategies to evaluate and determine their effectiveness are not yet developed.(*3*) There are no AMFs at this time.

Applying Safety Principles to the Planning and Design of Residential Neighborhoods and Commercial Areas

This section examines examples of residential and commercial planning issues that have received at least some safety analysis.

Discussion: Safety in the design and planning of residential areas

A list of principles has been proposed for new street patterns with a view to reducing accidents (*10*,*12*). The principles relevant to SCP for residential areas include:

- Differentiation of streets according to traffic function (clear distinction between arterial and local roads) with through traffic discouraged or eliminated, as introduced in Section 7.2.1 on self-explaining roads;
- Provision of facilities for motor vehicles, pedestrians and bicyclists including extensive pedestrian and bicycle networks and grade separated walkways to take pedestrians to bus stops on main roads;
- Consideration of the elderly road user;
- Layout designed to encourage low speed driving with driving at walking pace speed in some cases. Layouts are likely to include cul de sacs and very short streets (no longer than 100 m);
- No private driveways on arterial roads;
- Layout designed to discourage on-street parking as parked cars may increase risk of accidents;
- Small neighborhoods (about 500 houses) with no external traffic;
- Numerous playgrounds and green space areas available, traffic free;
- Separation of residential zones by car-free areas;
- Exclusive bus-ways; and
- Creating safe routes to school including connectivity with transit and other modal transfers, and appropriate site planning (for example, one ingress and one egress at school).

In the 1950s and 1960s, various British New Towns were constructed, often with many of the above principles in mind, especially extensive pedestrian and bicycle networks and/or exclusive bus-ways. The Traffic Safety Toolbox (1999) noted a greatly improved “safety index” in the New Towns compared with “old” (and larger) towns ((*18*), pg 23). Cul de sacs were found to be five to ten times safer for pedestrians, and especially for children, than other street patterns (Bennet G.T. and Markland J., “Road Accidents in Traditionally Designed Local Estates. Supplemental Report 394”, 1978 quoted by (*18*)). The Traffic Safety Toolbox also noted similar findings in Sweden.

Houten, Holland (population 32,000) was designed in 1979 using many of principles listed above. The town has twice as much bicycle and public transport use and 25% less car use than similar towns. Road traffic injuries are 70% lower than the national average in Holland and no fatalities have been reported ((*18*), pg 25, quoting: Kray J.H., “Dutch Approaches to Surviving with Traffic and Transport. Transport Review”, 1996).

Discussion: Safety in the design and planning of commercial areas

Most road users reach commercial areas using urban collectors and arterials. Dijkstra points out that although the speed recommendation of 18 mph (30 km/h) for residential streets is well established, the speed and safe design elements of "urban main/distribution roads are unknown or are at least not very clear" ((*16*), pg 61). Unknowns include network issues such as the network structure, the distance between junctions, and sight distances. Dijkstra favors the limited access type of network structure due to the decreased junction density which "will have a positive effect on the accident rate" ((*16*), pg 64).

Many factors are involved in creating overall principles for the safe design and speed recommendations for the network of urban collectors and arterials including road geometry (e.g., lane width and presence or absence of turn lanes and physical medians), operating speeds, and driveway and intersection traffic volumes.

With the increasing trend towards large stores providing a regional point of commerce attracting customers from various residential areas, it is important to have a systematic approach with early planning of the transportation network and the buildings in the commercial area. The site design may minimize the risk of conflicts both when vehicles approach the shopping area and when vehicles are within the shopping area by safely integrating the needs of vehicles, pedestrians, deliveries, parking, and buildings. Those who use the shopping area need accessibility to the shopping areas and safe and convenient circulation within the shopping area.

Although no quantitative information has been found on the design of shopping areas and their safe placement in the network, some safety conscious guidelines are presented:

- Intersections with municipal roads are provided at suitable locations that take into account the safety effects of different traffic volumes and speeds;
- Sequential decision making – as drivers reach the shopping area, the design of access points and other features follow a one-decision-at-a-time process:
  - Advance signing provides clear information allowing the driver time to select the shopping area as their destination and enter at the most appropriate access point;
  - On entering the shopping area, the driver is provided with the necessary information for reaching the specific store required. The route that provides access to a suitable parking lot near the destination is clearly distinguished. (Similarly, truck access points are clearly marked and differentiated from general public access); and
  - Once in the parking lot, the layout and choice of aisles provide customers with clear visibility of the area, avoiding confusion and frustration, and reducing driver delay.
- Driver expectations are met because the site design is similar to the design of other commercial sites;
- Roadways within the shopping area are consistent with urban roadway standards and treated like municipal roadways with respect to signs, and markings. Where possible, standard roadway geometry and lighting are used;
- Clear circulation routes provide safe, convenient and efficient circulation, minimizing conflict points and risk;
- Pedestrian routes are planned to encourage pedestrians to use sidewalks, crossings and properly designated areas to minimize conflicts with vehicles;
- Truck access and loading are separate from shoppers and their vehicles; and

- Parking provides suitable aisle width for safe maneuvering in and out of a parking stall, varied types and dimensions of parking stalls for users such as expectant mothers or family parking spaces, and the provision of handicapped parking stalls in accordance with the Americans with Disabilities Act (*25*).

Summary

The actual and perceived safety of many residential neighborhoods has deteriorated over the years as higher traffic volumes and higher operating speeds through wide residential streets have increased the number and severity of accidents. Reduced traffic volumes and lower speeds in residential areas are essential to the safety of local pedestrians, children, the elderly and bicyclists, all of whom are particularly vulnerable road users. Similarly, decreasing safety has been recorded along collectors and arterial streets used to reach major destinations such as schools and commercial areas. Two important approaches to improve the safety of the road network are self-explaining roads and safety conscious planning.

Self-explaining roads are designed to make the function, role and appropriate speed of a road immediately clear, recognizable and self-enforcing. Road design can complement and reinforce road users' perception of residential road environments in a way that encourages drivers to adjust their speed and in a way that encourages all road users to adjust their behavior appropriately. Holland has made considerable investments in self-explaining roads especially in residential areas, and designated areas are being expanded following clear procedures. The speed limit for residential self-explaining roads is 18 mph (30 km/h). Procedures for making self-explaining collectors and arterials remain less clear and are under development.

Safety conscious planning (SCP) involves the explicit, proactive and comprehensive implementation of measures known to improve safety. SCP is multimodal and concerned with the entire transportation network rather than localized problem areas only, although specific land and site planning with explicit safety in mind forms part of the comprehensive approach. The approach is intended to work towards a transportation network that is inherently safe and which avoids the need for mitigation projects to treat unsafe roadway conditions.

Self-explaining roads and safety conscious planning are relatively new and ambitious concepts intended to create broad and consistent road safety design principles for application in residential and commercial areas. Self-explaining roads in Holland have produced encouraging results with fewer vehicle movements and a 30% reduction in accident casualties in pilot areas, but there is limited quantitative information available as yet for assessing the impact of the concepts. Continuing evaluation and research are required to develop the guidelines needed to be able to correct the safety problems of existing areas, to ensure that safety problems are not built into future residential and commercial areas, and to quantify the safety impact of medium and high level planning decisions on different types of network, different road types, and various traffic volumes.

7.3. One-Way Systems and Turn Restrictions

One-way operations may include an area-system where all or most streets are affected, and may include corridor-systems where there are only a limited number of one-way streets. One-way systems may be found in both downtown and residential areas. Some one-way streets pass through both kinds of land use.

One-way operations are usually introduced to increase traffic capacity. One-way operations can improve safety under certain conditions (*18*).

One-way systems require careful thought and attention in their planning, design, and implementation to ensure that safety is maximized and that unintended consequences are avoided. Issues include the geometrics at the beginning and end of one-way segments, tapers, regulatory signs throughout, pavement markings, and suitable accommodation of turning movements at the beginning and end of one-way segments (*18*). One-way operations also require careful attention to their effect on the network surrounding them and the possibility that accidents are transferred to the neighboring area.

This section examines the safety impact of one-way operations and turn restriction in urban areas. The impact of closing streets and/or restricting traffic is also discussed.

Exhibit 7-4: Resources examined to investigate the safety effect of one-way operations

DOCUMENT	DESCRIPTION	COMMENT
(*26*) (Campbell, B. J., Zegeer, C. V., Huang, H. H., and Cynecki, M. J., "A Review of Pedestrian Safety Research in the United States and Abroad." FHWA-RD-03-042, McLean, Va., Federal Highway Administration, (2004))	Synthesis of past research, focused on pedestrian safety.	Added to synthesis.
(*27*) (Berkovitz, A., "The Marriage of Safety and Land-Use Planning: A Fresh Look at Local Roadways." Washington, D.C., FHWA, (2001))	The study examines the role that land-use planning plays in reducing traffic-related crashes, particularly for pedestrians and bicyclists.	Added to synthesis. Little or no quantitative information.
(*18*) (Institute of Transportation Engineers, "The Traffic Safety Toolbox: A Primer on Traffic Safety." Washington, D.C., ITE, (1999)).	The Institute of Transportation Engineers' Safety toolbox is a primer on many aspects of traffic safety, representing the personal knowledge, experience and expertise of members on how safety may be improved.	Added to synthesis. Little or no quantitative information.
(*28*) (Hart, J., "Converting Back to Two-Way Streets in Downtown Lubbock." Washington, D.C., ITE, (1998))	The study investigated the conversion of one set of one-way streets to two-way streets in the central business district of Lubbock, Texas	Added to synthesis. Little or no quantitative information.
(*29*) (Stemley, J. J., "One-Way Streets Provide Superior Safety and Convenience." Washington, D.C., ITE, (1998))	The study discusses the advantages and disadvantages of one-way streets and concludes that the advantages outweigh the disadvantages.	Added to synthesis. Little or no quantitative information.
(Institute of Transportation Engineers, "Traffic Engineering Handbook Fourth Edition." Vol. 4, Englewood Cliffs, N.J., Prentice-Hall, Inc., (1992))	The Institute of Transportation Engineers' Handbook brings together the state of the art in established transportation engineering practice.	Not added to synthesis.

Discussion: Conversion of two-way streets to one-way streets

Little quantitative information is available on the conversion of two-way streets to one-way streets. Both the qualitative and quantitative comments found in the literature are sometimes contradictory.

One-way systems have the following potential operational benefits:

- Elimination of two-way traffic conflicts on a street;
- Reduction in the large number of potential conflicts at intersections in a two-way system and eliminate left-turns of opposing traffic;
- Simplification of all turns;
- Possible reduction in waiting times for pedestrian at signals;

- Simplification of traffic control at intersections; and
- Facilitation of traffic signal synchronization and reduction in congestion. Platoons of traffic moving at the appropriate speed may travel the length of the street with few or no stops.

The following statements found in current literature provide some insight into the potential benefits of one-way systems in terms of general safety:

- Reduced congestion and fewer conflicts between traffic flows mean that "conversion to one-way operations can …. have a significant impact in improving safety as well as reducing congestion" (*18*);
- Reduced congestion may "bring about a reduction in rear-end accidents" (*18*). "Head-on and left-turn-from-the-street accidents between intersections will virtually disappear" (*29*);
- "Numerous studies have shown that the conversion of two-way streets to one-way operation reduces total accidents [by] 10 to 50 percent" ((*29*), pg 330-337). (This finding is taken from a 1967 study by Bruce, "One-way Major Arterial Streets. Improved Street Utilization through Traffic Engineering".);
- "A well planned and carefully designed system of one-way streets can be one of the most effective means of reducing accidents in an urban street network" ((*18*), pg 127, referring to Pignataro "Traffic Engineering Theory and Practice", 1973);
- Stemley mentions a New York City study (Karagheuzoff, 1972) that "reported an average reduction of 22 percent in intersection accidents after conversion to one-way street pairs in New York City" (*29*); and
- "The simplified operation of one-way streets is particularly helpful to elderly drivers and pedestrians [who] generally have slower perception and reaction times and reduced eye movements while searching the environment" (*29*).

One-way streets may provide potential benefits in terms of pedestrian safety, such as:

- Pedestrians deal with only one direction of traffic and may be less likely to take risks crossing the road as waiting times are reduced by simplified signal phasing at intersections ((*18*), pg 127, (*29*)); and
- Stemley mentions a New York City study (Wiley, 1959) that "found a 25 percent reduction in intersection pedestrian accidents at one-way street intersections after conversion from two-way operation" (*29*).

Potential safety concerns with one-way systems include:

- Increased vehicle speed;
- Increased sideswipe accidents due to increased weaving (from lane to lane or when finding a parking space);
- Inconvenience for drivers who must drive one or more blocks out of their way to reach their destinations;
- Possible confusion, difficulty and delay in reaching the destination, especially for drivers new to the area;
- Difficulties for pedestrians crossing fast moving traffic;
- Longer walks for bus users to reach destinations and bus stops;
- Confusion among some bus users when finding the return service; and
- Emergency vehicle operation through one-way street systems.

Discussion: Conversion of one-way streets back to two-lane, two-way streets

Stemley (1998) noted that many one-way street systems were introduced 30 or 40 years ago before many downtown city areas declined, losing retail activity and losing pedestrian and vehicular and volumes. “Even in cities where congested streets now exist during many hours of the day, critics of a one-way street system recite perceived disadvantages, believe that the disadvantages outweigh any advantages and argue a change must be made for the good of the community” (*29*). Stemley supports one-way systems and concluded that “by changing to a two-way system, a large backward step will be taken which will result in a downtown that is less inviting than it is now” (*29*).

Berkowitz, however, discusses a case of a pair of one-way streets where the problems associated with the one-way system led to the streets being rebuilt and converted back to two-lane, two-way streets (*27*). In this example, the pair of one-way streets passed through the town's business district. The streets also passed through a residential area. Each street had three 11 ft (3.4 m) wide lanes with parallel parking allowed on both sides of the street except during rush hours. The average traffic speed was almost 35 mph (56 km/h). In the business district, there were traffic signals at intersections; in the residential area, the cross streets were stop-controlled. Most accidents along this corridor were sideswipes and rear-ends at the signalized intersections, or sideswipes associated with traffic turning or crossing from the cross streets. Almost all of the accidents were property damage only crashes, and a few resulted in injury. Residents complained about high-speed traffic passing through their neighborhood and children having to cross one or both of the major thoroughfares if they walked to school (*27*).

The one-way streets were both converted to two-lane, two-way streets with a 10.5 ft (3.2 m) lane in each direction, two 5.5 ft (1.7 m) bike lanes, and parallel parking without rush-hour restrictions on both sides of the street. The sidewalks were widened, and some trees and benches were added in the business district. “Zebra” patterned crosswalk markings with pedestrian warning signs were added to the two intersections closest to the school. The average speeds came down to about 25 mph (40 km/h). Berkovitz notes that the number of accidents remained about the same, but fewer resulted in injuries. Travel times for commuters by car increased slightly, but the number of bicyclists and pedestrians increased. In addition, some vehicular traffic was diverted to alternate routes (*27*).

In Lubbock, Texas, some one-way streets were converted back to two-way streets in 1995 due to business concerns and “the inconvenience of downtown travelers [having] to go several blocks out of the way to drive in the direction of their choice” (*28*). The change back to two-way streets was popular with the business community. The City of Lubbock found that “the number of accidents has increased by a small margin, but it has been no greater than the fluctuation from year to year” (*28*).

Discussion: Traffic Restrictions and Street Closures

Town centers and residential areas sometimes close streets to traffic or implement traffic restrictions. As noted in Campbell et al. (2004), a study in Upsala, Sweden by Lovemark (1974) evaluated certain downtown streets where some streets were closed to vehicles or subject to traffic restrictions (*26*). Defining “pedestrian risk” as the probability of a personal injury crash that could be predicted from serious traffic conflicts for various types of pedestrian and motorist behaviors, it was found that pedestrian risk declined 29% in the study area. Surrounding streets that were not affected by the traffic restrictions experienced a 30% increase in vehicular volume after restrictions were imposed, and a 12% increase in pedestrian risk (*26*).

Similar street closures and traffic restrictions in 19 areas of London (Brownfield et al., 1980 as cited in (*26*)) resulted in reduced pedestrian accidents at ten of the sites. Pedestrian crash rates remained stable at two locations. Overall, pedestrian crashes declined by 24.4%, although this change was not statistically significant.

Summary

The safety effects of one-way systems are not well documented either for the streets directly affected or for the surrounding area. The balance between the safety advantages and disadvantages of one-way systems compared with two-way systems is unclear.

Although one-way systems may lead to a reduction in accidents through reduced congestion and simplified turning movements, one-way systems can also lead to increased vehicle speeds and longer trips as some drivers may have to make additional turns and drive additional distances to reach their destination. The needs of pedestrians and transit users who may experience difficulties negotiating one-way systems may be a key consideration.

It is likely that the closure of streets to motorized traffic has an effect beyond the site. The overall effect for all road users is not known.

7.4. Area Wide Traffic Calming

As described in the Traffic Engineering Handbook, “the broadest interpretation of the term “traffic calming” has now expanded to mean the various ways of reducing the motor vehicle intrusion into and effects on urban life” ((*31*), pg 259). Traffic calming under this definition comprises a “process and a desired outcome” (*31*). Making safety an explicit and integral part of the long and short-range planning of metropolitan areas (Section 7.1), and the planning and design of residential and commercial areas (Section 7.2) will lead to an urban form consistent with the broadest definition of traffic calming, and to a safe, harmonious and integrated network for all road users.

Litman states that traffic calming which significantly reduces traffic speeds typically reduces crashes by 40%.(*7*)

Three levels of traffic calming are defined in ITE’s Traffic Engineering Handbook:

- Level III (Metropolitan) Traffic Calming involves a global network planning approach of setting objectives with strategies and actions designed to achieve the goal of a reduction of travel. The metropolitan level of traffic calming can only be achieved by introducing appropriate measures into long and short-range plans (Section 7.1);
- Level II Traffic Calming relates to measures that bring the explicit consideration of safety to modifications to existing cross sections and land use adjacent to the arterial road system; and
- Level I Traffic Calming refers to the traditional approach to site-specific calming techniques and traffic calming deployed to the local street system.

Most area-wide traffic calming schemes focus on the management of vehicles by means of physical devices, and are typically found in residential areas, with the purpose of reducing traffic volume and driving speed on residential access roads (Level I). Numerous measures can be used to reduce traffic volume and driving speed: systems of one-way streets, street closures, vehicle restrictions, lane narrowings, bike lanes, mini-circles, speed humps, raised crosswalks, chicanes, rumble strips, pavement treatments, etc.

This section describes the safety effects of area-wide traffic calming schemes, mostly at the Level I classification of measures, as defined above. Many studies have evaluated the safety effects of area-wide traffic calming. Some researchers have made strong claims regarding the safety of traffic calming, but the type of traffic calming and the circumstances tend to be unclear(*7*). Much of the quantitative work on Level I traffic calming is European.

Exhibit 7-5: Resources examined to investigate the safety effect of area wide traffic calming

DOCUMENT	DESCRIPTION	COMMENT
(*32*) (Bunn, F., Collier, T., Frost, C., Ker, K., Roberts, I., and Wentz, R., "Area-wide traffic calming for preventing traffic related injuries (Cochrane review)." The Cochrane Library, No. 3, Chichester, UK, John Wiley and Sons, (2004))	Re-analysis of Elvik (2001).	Added to synthesis.
(*33*) (Christensen, P., "Area wide urban traffic calming schemes: re-analysis of a meta-analysis." Working paper TØ/1676/2004, Oslo, Norway, Institute of Transport Economics, (2004))	Re-analysis of Elvik (2001).	Added to synthesis.
(Forbes, G., "Synthesis of Safety for Traffic Operations: Final Report." Ottawa, Ontario, Canada, Transport Canada, (2003))	Synthesis presenting the best available evidence respecting the safety impacts of traffic operations	No new quantitative data. Not added to synthesis.
(*34*) (Elvik, R., "Area-wide Urban Traffic Calming Schemes: A Meta-Analysis of Safety Effects." Accident Analysis and Prevention, Vol. 33, No. 3, Oxford, N.Y., Pergamon Press, (2001) pp. 327-336.)	Meta-analysis of 33 studies evaluating the safety effects of area-wide urban traffic calming	Added to synthesis.
(*31*) (Institute of Transportation Engineers, "Traffic Engineering Handbook Fifth Edition." Washington, D.C., Institute of Transportation Engineers, (1999))	The Institute of Transportation Engineers' Handbook brings together the state of the art in established transportation engineering practice.	Added to synthesis.
(Ewing, R., "Impacts of Traffic Calming." Transportation Quarterly, Vol. 55, No. 1, Washington, D.C, Eno Foundation for Transportation Inc., (2000) pp. 33-46.)	This paper quantifies the kinds of impacts resulting from traffic calming measures of various types	Not reviewed. Duplicates report FHWA-RD-99-135 (see below)
(Ewing, Reid, "Traffic Calming: State of the Practice." Washington, D.C., Institute of Transportation Engineers, (1999))	An extensive document about the many aspects of Traffic Calming; Pg 109-112 – safety impact of traffic calming is briefly discussed. The author notes that all studies have not controlled for RTM and other factors.	Not enough information or data offered for AMF estimates – Not added to synthesis
(Catalano, V. V. and Schoen, J. M., "Neighborhood Traffic Management in Tuscon, Arizona." Chicago, Ill., Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations and Opportunities, (1997) pp. 21-27.)	Report based on a 5-year history of actual program evidence from technical studies and neighborhood input	No AMFs. Not added to synthesis.
(Zein, S. R., Geddes, E., Hemsing, S., and Johnson, M., "Safety Benefits of Traffic Calming." Transportation Research Record 1578, Washington, D.C., Transportation Research Board, National Research Council, (1994) pp. 3-10.)	Conducted a study of the safety benefits of traffic calming at four sites in Vancouver; also reviewed 85 case studies from Europe, Australia and North America	Reviewed by Elvik 2001. Too few data to be included in meta-analysis. Not added to synthesis.

Rather than reviewing each of these studies, this section will rely on three meta-analyses that have been made of relevant evaluation studies. These meta-analyses include one made by Elvik (*34*), a re-analysis of Elvik's analysis by Christensen (*33*), and a meta-analysis by Bunn et al. (*32*).

For the purposes of clarifying the terminology and data used in the studies presented here, the road system in an area is re-classified with some roads designated as main roads and others as local roads. Traffic calming measures are applied on local roads, whereas main roads are often upgraded to serve larger traffic volumes without an increase in accidents. Local roads are usually residential streets with two lanes and curb parking with a traffic volume below 2,000 veh/day. Main roads are usually wider, and may be two-lane or multi-lane undivided roads with a traffic volume between 5,000 and 30,000 veh/day. Land use along main roads is usually more commercial than the land use along local roads. A common speed limit is 31 mph (50 km/h). In general, the upgrading of main roads tends to rely on inexpensive measures like parking prohibitions, restrictions on turning movements at intersections and upgrading of traffic signals. These projects can be classified as Level I traffic calming measures. ((*31*), Table 9.1, pg 261).

Exhibit 7-6 lists the main findings of the three meta-analyses of studies that have evaluated the safety effects of area-wide traffic calming schemes.

Exhibit 7-6: Estimates of the effects on accidents of area-wide traffic calming schemes according to three meta-analyses of evaluation studies

Data summarised	Area and accidents influenced	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Meta-analysis by Elvik (2001)			
Best studies (10 estimates)	Whole area, injury accidents	0.890	0.050
Best studies (9 estimates)	Local roads, injury accidents	0.820	0.119
Best studies (9 estimates)	Main roads, injury accidents	0.934	0.061
Best studies (5 estimates)	Whole area, PDO accidents	0.861	0.038
Best studies (3 estimates)	Local roads, PDO accidents	0.729	0.109
Best studies (3 estimates)	Main roads, PDO accidents	0.952	0.060
Re-analysis of Elvik (2001) by Christensen (2004)			
Estimate generated by meta-regression model	Whole area, injury accidents	0.830	0.110
Estimate generated by meta-regression model	Local roads, injury accidents	0.820	0.267
Estimate generated by meta-regression model	Main roads, injury accidents	0.750	0.194
Estimate generated by meta-regression model	Whole area, PDO accidents	0.800	0.092
Estimate generated by meta-regression model	Local roads, PDO accidents	0.700	0.240
Estimate generated by meta-regression model	Main roads, PDO accidents	0.730	0.163
Meta-analysis by Bunn et al. (2004)			
Before-after with comparison group (8 estimates)	Whole area, fatal accidents	0.625	1.340

Meta-analysis by Bunn et al. (2004)			
Before-after with comparison group (16 estimates)	Whole area, injury accidents	0.890	0.102
Meta-analysis by Bunn et al. (2004)			
Before-after with comparison group (8 estimates)	Whole area, all accidents	0.950	0.145
Before-after with comparison group (8 estimates)	Whole area, pedestrian accidents	1.000	0.156

Elvik (2001) classified studies by the study design employed. Before-and-after studies using a matched comparison group were rated as best. If adequately matched by previous accident history, these studies will control both for regression-to-the-mean and long-term trends in safety (*34*). Unfortunately, not all studies provide enough details to assess how closely the treated sites were matched to the comparison sites. In the British “Urban safety project”, which was included among the meta-analyzed studies using a matched comparison group, treated sites were very carefully matched to comparison sites with respect to both the number of accidents and past accident history. Studies were rated as medium high quality and the standard errors were adjusted by a factor of 1.8. This adjustment was also applied for the analyses reported by Christensen (*33*) and Bunn et al. (*32*).

According to the meta-analysis reported by Elvik (2001), area-wide traffic calming is associated with a reduction of the number of injury accidents of slightly more than 10% (*34*). There is a larger reduction on local streets than on main streets. Accidents resulting in property damage only go down by nearly 20%; again the largest reduction is found for local streets. Somewhat surprisingly, the accident reduction appears to be larger for property-damage-only accidents than for injury accidents. This is surprising, because speed-reducing measures are an important element of area-wide traffic calming. One would normally expect a reduction in speed to have a greater impact on injury accidents than on property damage only accidents.

Christensen (2004) re-analysed Elvik’s study, applying techniques for meta-regression analysis (*33*). Based on the coefficients estimated in the meta-regression analyses, Christensen generated estimates of the effects of traffic calming based on coefficients describing study design and the decade when a study was reported. The estimates presented in Exhibit 7-6 refer to before-after studies employing a matched comparison group and published after 1990. Christensen found an accident reduction in all the study design and decade groupings that were specified. The estimates are, however, somewhat inconsistent, in that the estimated effect for both local streets and main streets tends to be larger than the estimated effect for the whole area. This appears as inconsistent, because, in the conventional meta-analysis as performed by Elvik (2001), the effect for the whole area is the weighted mean (or sum) of the effect for local streets and main streets. One would expect the safety effect for the whole area to lie somewhere between the effect found for local streets and the effect found for main streets.

Bunn et al. (2004) performed a meta-analysis of area-wide traffic calming projects, including only before-and-after studies that employed a comparison group (although not necessarily a matched comparison group) (*32*). They estimated a reduction of 37% in fatal accidents, 11% in injury accidents and 5% in all accidents. Judging by the raw numbers presented in the study, the last category (all accidents) is likely to consist mostly of property damage only accidents. For pedestrian accidents, Bunn et al. did not find an effect of area-wide traffic calming.

The findings of these analyses for injury accidents are broadly consistent. For the whole area affected, one may expect traffic calming to reduce injury accidents by some 10 to 15%. The summary estimates of effect for property damage only accidents are less consistent. Elvik (*34*) and Christensen (*33*) find indications of a larger effect for property-damage-only accidents than for injury accidents; Bunn et al. find indications to the contrary. In view of the fact that speed reduction is a key element of traffic calming, the finding of Bunn et al. (*32*) is more consistent with what is otherwise known about the impacts of reducing speed than the findings of Elvik and Christensen.

7.5. Access Management Policy

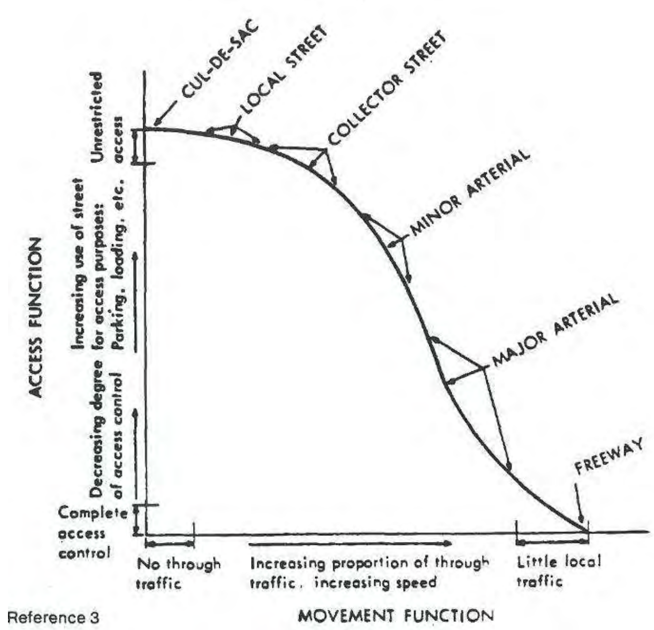
Access management is a set of techniques designed to manage the frequency and magnitude of conflict points at residential and commercial access points. The purpose of an access management program is to balance the required mobility of a roadway facility with the accessibility needs of adjacent land uses (*35*). The management of access, namely the location, spacing, and design of private and public intersections, is considered to be one of the most critical elements in roadway planning and design. Access management provides or manages access to land development while simultaneously preserving traffic safety, capacity, and speed on the surrounding road system, thus addressing congestion, capacity loss, and accidents on the nation's roadways (*31*).

As described in the AASHTO's "A Policy on Geometric Design of Highways and Streets" the two major considerations in classifying highway and street networks functionally are access and mobility. Along with the idea of traffic categorization is the dual role of the highway and street network in providing access to the surrounding properties, and travel mobility. While access is a fixed need for every area served by the highway system, mobility is provided at varying levels of service and is typically represented through the operating speed or trip travel time (*36*). Where maximum efficiency of traffic movement is achieved, direct access to the roadway is limited. Conversely, imposing minimal restraint on roadway access reduces the safe, efficient movement of through traffic (*37*).

The relationship of the two functions relative to the functional classifications of the roadway system is illustrated in Exhibit 7-7. Full access control means that preference is given to through traffic by providing access connections by means of ramps with only selected public roads and by prohibiting crossings at-grade and direct private driveway connections. With partial control of access, preference is given to through traffic to a degree and access connections, which may be at-grade or grade-separated, are provided with selected public roads, and private driveways. In general, full or partial access, control is accomplished by legally obtaining the access rights from the abutting property owners, usually at the time of purchase of the right-of-way, or by the use of frontage roads (*36*).

With freeways, where the safety and efficiency of traffic movement are highest priority, highway designers and administrators typically have had little trouble defining the need, policies and standards needed to obtain the necessary control of access. Likewise, at the other end of the scale, property access is clearly the dominant characteristic of local streets such as cul-de-sacs and the policies, design and operational characteristics are easily tailored to reflect this priority. Difficulty arises when trying to balance access and mobility for the roadway system lying between the two extremes (such as arterials and collectors), and this is reflected in the greatly varying policies and standards practiced by the various jurisdictions across the country. A balanced, comprehensive access management program which provides reasonable access while maintaining safety and efficiency in traffic movement is needed (*37*).

Exhibit 7-7: Relationship between access control and traffic movement (37)



Two definitions are particularly relevant to this section of the HSM: access point, and access-point density. The Highway Capacity Manual (2000) defines the following terms (*38*):

- Access point: "an intersection, driveway, or opening on the right-hand side of a roadway. An entry on the opposite side of a roadway or median opening also can be considered as an access point if it is expected to influence traffic flow significantly in the direction of access"
- Access-point density: "the total number of access points on a roadway divided by the length of the roadway and then averaged over a minimum length of 5 km"

As presented in NCHRP Report 420, access management combines relevant road authority policy and the particular attributes of the roadway and access to assess alternatives and select the most effective choice of access design and operations. The safety of an access point depends on the inter-relationships between the corridor characteristics, other access points along the corridor, and its specific design and operations. Access design principles should be applied and coordinated with the three components of the access system. These components include the public roadway, the access (via the driveway or public street), and the land use itself. All three components have to be treated as integral parts of an overall system because neglecting any one would merely transfer a problem to one of the others (*31*).

Although access management techniques have evolved over time, they can generally be divided into two categories: techniques that control access through changes in policies; and techniques that control access through changes in the design of the roadway or the operations. The two categories can be further subdivided into the following (*39*):

- Policy – Management:
  a. Access codes/spacing
  b. Zoning/subdivision Regulations
  c. Purchase of Access Rights
  d. Establishment of Setbacks from Interchanges and Intersections
- Design – Operations:
  a. Interchanges
  b. Frontage Roads
  c. Medians – Left turns
  d. Right turns
  e. Access/Driveway Location (Retrofit, Consolidation, Reorientation, Relocation)
  f. Traffic controls
  g. Access/Driveway Design

An extensive TRB website containing access management information is available at www.accessmanagement.gov.

Intersections, segments, and the safety effect of various design elements are discussed in great detail in Chapters 3 and 4, and there are inevitable links between those chapters and this section. Relevant links to those Chapters are identified in the following discussion.

The following sections discuss the safety impact of the various access management techniques that fall under the categories identified previously. More specifically, the safety implications of providing residential and commercial access are addressed within the context of the roadway network (policies and planning), the roadway segment or corridor (density, road class and environment, the presence of medians, alignment versus offsetting of opposite driveways, proximity to intersections, etc.), and of various design elements related to the control of access (median type, permitted entry/exit movements, left-turn entry, right-in/right-out, storage, sight clearance, etc.).

7.5.1. Access Control and Road Function

Highway and street networks are functionally classified using two key considerations: access and mobility. Highways have a dual role, providing travel mobility on the road network, and also providing access to the surrounding properties. On roads designed for high levels of service, direct access is limited or not allowed.

The relationship between access control and traffic movement can be divided into three main types:

1. Full access control is found on freeways. Preference is given to through traffic by prohibiting at-grade crossings and direct private driveway connections, and by providing access only by ramps which connect with selected public roads.
2. Partial access control is typical of collectors and arterials. Preference is given to through traffic, but connections are provided with selected public roads and private driveways. The connections may be at-grade or grade-separated.
3. Unrestricted access control is provided on local streets.

Most challenges associated with access control arise when balancing access and mobility on collectors and arterials. These challenges are reflected in the greatly varying policies and standards practiced by the various jurisdictions across the country.

The policies of road authorities, which form an extension of the planning policies (and subsequently, the explicit safety) for the road network, as discussed in Section 7.1, provide the basis for the key elements of access management. That is, for each of the road classes defined in an agency's policies, guidelines and standards may be established for limiting driveways and restricting movements, defining the spacing between driveways, and many other elements related to access management. Note that although Gluck et al. grouped access spacing together with access codes and classified the combination as one of the four policy-related access management techniques (*39*), access spacing and other policy-related access management techniques are addressed in separate sections.

Previous research studies have established that the overall safety of a roadway segment is generally thought to be dependent on the access spacing and number of driveways/intersections present (*40*). **In the context of the HSM, access points include minor intersections (e.g., three-leg unsignalized) as well as private driveways, and a roadway segment is defined as the road between two major intersections.**

7.5.2. Access Management Policies and Road Network Safety

Access management policies, such as establishing an access management code, modernizing zoning requirements, and acquiring rights-of-way, are extremely important and provide a basic framework for other access management techniques. In essence, these policies balance the rights of property owners to have reasonable access to the general system of streets and highways with the rights of road users to freedom of movement, safety, and the efficient expenditure of public funds. The policies and recommended access guidelines balance these competing rights. The goal is to manage access to land development while simultaneously preserving the flow of traffic on the public road system in terms of safety, capacity, and speed (*41*).

Flora and Keitt state that the development and adoption of an access management policy is the first essential step toward effective access management. This policy establishes the goals of the access management program and defines the mechanisms through which the goals will be accomplished (*37*). However, because of their broad nature, policies generally do not lend themselves to measurement or quantification (*39*). Gluck et al. identified four groups of access management techniques related to access management policies (*39*):

- Access codes/spacing
- Zoning/subdivision regulations
- Purchase of access rights
- Establishment of setbacks from interchanges and intersections

One important aspect of an access management policy is the legal basis which it may create. Through a realistic statement of objectives and goals, access management is tied to the transportation needs and welfare of the public at large. An access management policy also provides for more uniform application of regulatory measures, thus minimizing the argument by many opponents that they are being arbitrarily discriminated against (*37*).

According to AASHTO's "Policy on Geometric Design of Highways and Streets", policy-related access control techniques can be implemented with two basic legal powers: police power and eminent domain. The first provides the state with sufficient authority for most access control techniques associated with highway operations, driveway location, driveway design, and access denials. The second allows a state to take property for public use provided that the owner is compensated for the loss (*36*). While the owner of abutting property is entitled to a reasonable degree of access, that owner is not entitled to direct access to new limited access highways to freeways (*37*). Highway agencies usually have the power to deny access through the use of police power when reasonable access is available (*36*). A state may need to use eminent domain when building local service roads, buying abutting property, acquiring additional right-of-way, and taking access rights.

This section discusses the safety effect of policies related to the provision of access points along different road classes, and the different policies governing the planning of road networks from the perspective of policy issues such as setback distances and corner clearances.

No AMFs were found or calculated.

It is recognized that there are inherent difficulties associated with measuring the safety impact of access management policy changes to whole road networks since changes in how the network is defined (i.e., the boundary of the network itself) will directly affect the outcome of the analysis. Nevertheless, it is foreseeable that the safety effect of policy changes to roadway segments and specific corridors be quantified. Future research should aim to present quantitative information in the context of road types and volumes, road environment and accident types and severity.

As noted earlier, policy-related access management treatments or techniques are inherently difficult to quantify or measure. None of the studies reviewed provided sufficient information to develop indices of effectiveness or standard error values. Some qualitative and anecdotal evidence was found, the majority of which focused on conflicts and not accidents.

Discussion: Impact of different types of access control

Gattis compared accident rates at three similar and adjacent urban roadway segments with differing access controls in place (*42*). The roadway segment with the least access control had a high density of driveways, intersecting streets and median openings; the roadway segment with a moderate level of access control had frontage roads running parallel with the main roadway segment and fewer cross streets; and the roadway segment with the highest level of access control had few median openings, driveways, and cross streets.

Gattis reported that the roadway segment with the highest level of access control also had the lowest non-intersection and intersection, angle and sideswipe accident rates but the highest intersection and non-intersection rear-end accident rates. According to Gattis, the roadway segment with the highest level of access control had PDO accident rates about half that of the other two roadway segments, and total and injury accident rates that were about forty percent less than those of the other two segments.

Discussion: Access management policies at intersections in the vicinity of interchanges

Freeway interchanges provide the means to move traffic between freeways and arterial streets and have become focal points of activity in urban, suburban and even rural locations. As a result, interchanges draw large volumes of traffic and stimulate the development of the surrounding land. Although access is controlled on the freeway in the interchange area, there is often little or no access control along the arterial roads. Existing street intersections along the arterial are often located too close to interchanges and the problem is further compounded with curb cuts and median breaks to provide access to adjacent traffic generators (*39*).

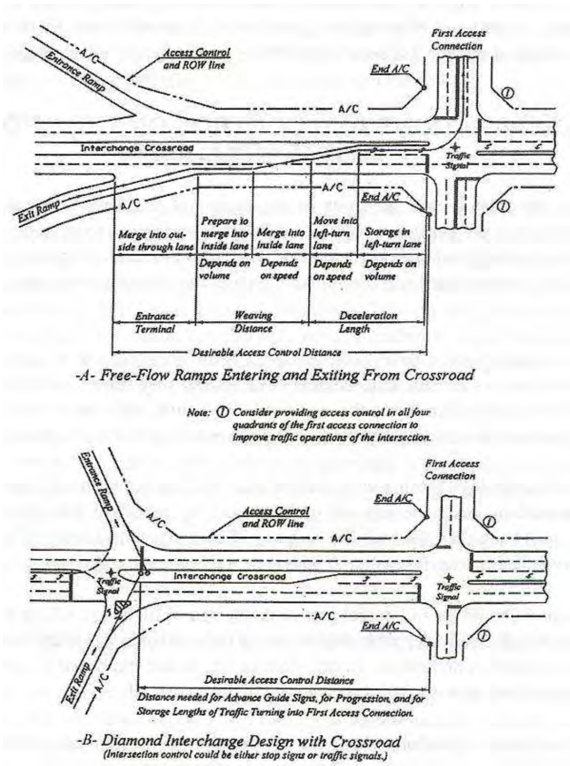
There is growing recognition that access separation distances and roadway geometry have to be better regulated from an access management perspective. According to NCHRP Synthesis Report 332, access management policies that are now typically in effect at interchanges address issues including access spacing standards, corner clearances, and also the use of medians (*35*).

With respect to access spacing for intersections in the vicinity of interchanges, there are three aspects that directly affect the management of access, namely: the appropriate spacing of the interchanges; the distance along the crossroad from an interchange ramp in which access should be restricted or eliminated; and the appropriate spacing of public and private accesses along the crossroad when close to interchange on-/off-ramps. Highway agencies currently use a wide range of factors to determine the appropriate spacing to the first access point downstream or upstream of the interchange terminal. These factors include the surrounding land use and environment, the classification of the crossroad, the interchange form, type of access point, downstream storage requirements, the design of the cross section, design speed, volume, cycle length, cost and economic impacts, functional role of the interchange and the jurisdiction of the crossroad. While it is generally recognized that controlling access at intersections in the vicinity of interchanges has the benefit of minimizing congestion, simplifying driving tasks, improving pedestrian and bicyclist safety and even reducing overall crash rates, it is unclear how each of the determining factors contributes to the overall safety of the road network adjacent to the interchange (*35*).

Although it has been established that numerous state departments of transportation rely on the 100 ft urban and 300 ft rural access spacing guidelines provided in the 1991 AASHTO publication, “A Policy on Geometric Design of Highways and Streets”, there appears to be no underlying rationale for these spacing requirements and the safety implications of adhering to or straying from these spacing requirements have not been established (*35*).

Recent research suggests a shift in state policy in response to contemporary guidance emerging recent research efforts from AASHTO and the Transportation Research Board (*43*). For example, the 2001 edition of AASHTO’s “Policy on Geometric Design of Highways and Streets” provides more extensive treatment of the subject of interchange area access control than previous editions. As illustrated in Exhibit 7-8, AASHTO not only addresses the importance of access control on interchange crossroads but also identifies elements to consider in determining appropriate access separations and access control distances in the vicinity of free-flowing ramps.

Exhibit 7-8: Access control elements along interchange crossroads (36)



The most recent update to the state of the practice in interchange area access management is found in the Transportation Research Board's Access Management Manual (TRB 2004), which expands upon previous research efforts conducted in NCHRP Report 420: Impacts of Access Management Techniques, and several other studies (*43*). As summarized in Exhibit 7-9 and Exhibit 7-10, and illustrated in Exhibit 7-11, these sources recommend access spacing standards for crossroads at freeway interchanges which are greater than the minimum provisions of AASHTO policy.

Exhibit 7-9: Suggested minimum access spacing standards [ft] for two- and four-lane roads at interchanges (39)

Two-Lane Crossroads

Access Type	Area Type		
	Full Developed Urban	Suburban	Rural
	(45 mph)	(45 mph)	(55 mph)
First Access	750	990	1,320
First Signalized Intersection	1,320	1,320	1,320

Four-Lane Crossroads

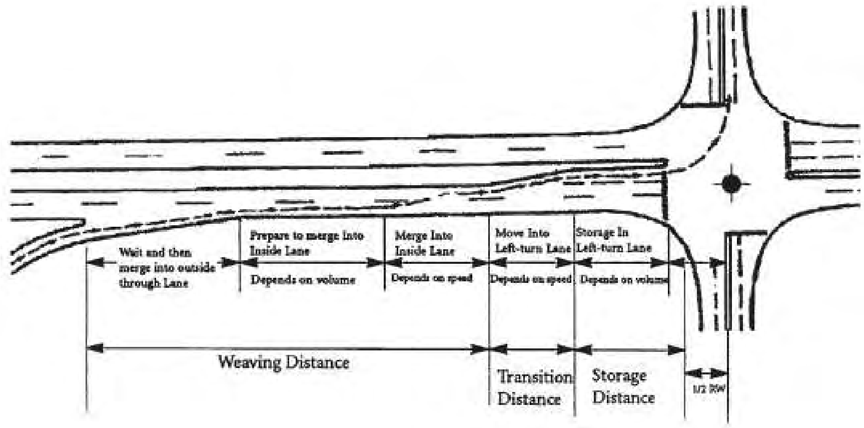
Access Type	Area Type		
	Full Developed Urban	Suburban	Rural
	(45 mph)	(45 mph)	(55 mph)
First Access from Off-Ramp	750	990	1,320
First Median Opening	990	1,320	1,320
First Access before On-Ramp	990	1,320	1,320
First Signalized Intersection	2,640	2,640	2,640

Exhibit 7-10: Suggested access spacing guidelines in the vicinity of interchanges (43)

Separation Distances from Interchange Exit Ramps

Weaving - Moving across through lanes	800 feet on two-lane arterials 1,200 on four-lane arterials 1,600 on six-lane arterials
Transition - Moving into turn lane(s)	150 to 200 feet
Perception-reaction distance	100 to 150 feet
Storage	Adequate for volume without overflow into through lane (typically 200 to 300 feet depending on demand)
Distance to centreline of intersection	40 to 50 feet

Exhibit 7-11: Factors influencing access spacing in the vicinity of interchanges (39)



One of the more critical factors identified in NCHRP Synthesis Report 332 is the design speed on roadway segments in the vicinity of the interchange. As expected, the higher the design speed, the greater the access spacing should be (*35*).

While the general relationships between design speed and required braking distance are understood, the safety impact of changing the policies related to the design speed on roadways near interchanges have not been quantified. In the absence of more definitive research results, evidence from existing studies that have evaluated the safety effects of changes to design speeds on the approaches to intersections will be used. With the prevalent presence of weaving and merging traffic, some of the risk factors for accidents are clearly different at intersections in the vicinity of interchanges compared to regular intersections. However, evidence regarding the safety effects of these treatments at regular intersections is perhaps the closest one can get to intersections in the vicinity of interchanges at this time. Additional information may be provided in future editions of the HSM. Interchanges are also discussed in Chapter 5.

Discussion: Regulate corner clearance

Corner clearances represent the minimum distances required between intersections and driveways along arterials and collector streets. Flora and Keitt defined corner clearance as the distance measured along the back of the arterial curb from the nearest edge of a driveway to the nearest edge of the intersection (*37*). As stated by AASHTO, "driveways should not be situated within the functional boundary of at-grade intersections. This boundary would include the longitudinal limits of auxiliary lanes" (*36*).

Through a review of existing policies related to corner clearances for various state, county and city agencies, Gluck et al. found that the requirements varied greatly from one jurisdiction to the next and ranged from as little as 16 ft to 350 ft. Although the safety effect of regulating corner clearance has not been quantified to date, as the authors point out, placing driveways too close to intersections correlates with higher accident frequencies and as many as one-half of all accidents involved are driveway-related (*39*).

With regards to network planning, ensuring adequate corner clearance can best be achieved before land subdivision and site development approval. Potential options to do so include (*35*):

1. Requiring property access from secondary roads;
2. Locating driveways at the farthest edge of the property line away from the intersection;
3. Consolidating driveways with adjacent properties; and
4. Installing a raised median barrier on approaches to intersections to prevent left-turn maneuvers.

Implementing these treatments can minimize driveway/intersection conflicts since they prevent the blockage of driveways upstream of an intersection by standing traffic queues.

7.6. Road-Use Culture

Road safety is affected not only by the engineering and planning decisions that create the transportation network used by travelers, but also by the road-use culture of the people using the network. Road-use culture refers to the different choices made by people as they respond to the network and to other users of the network. These choices vary with social group and geographical area. In Europe, where all EU countries apply similar countermeasures to improve road safety and all have regulations for speeding, DUI, and seat belts, the countries have very different success in reducing the number of accidents. For example, in 1996, the United Kingdom had 64 road accident fatalities per million people whereas Portugal had 274 road accident fatalities per million people (*44*).

While the choices may not be understood entirely, it is clear, for example, that the general level of patience and politeness or of impatience and aggression is likely to characterize the behavior of road users over a wide area. Familiarity will also play a role. In Holland, for example, bicyclists are fully accepted road users whereas elsewhere, bicyclists and even pedestrians may be perceived as an inconvenience on the road. Factors such as the level of enforcement and the efficiency of the supporting judicial system are also likely to have an effect in road use culture. Road-use culture affects motorists' decisions to drive above the speed limit, response to red-light cameras at intersections, behavior at all-way stops in a neighborhood, and every other aspect of driving behavior including acceptance and attitudes towards pedestrians and bicyclists. Pedestrians and bicyclists also use the transportation network in accordance with their own road-use culture and perception of how to behave and how to respond to the network and to other road users.

Zaidel has considered the role of safety interventions in relation to road-use culture and the interaction between individuals, groups and culture (*45*). Zaidel asks how an individual driver may influence the behavior of other drivers, how other drivers may affect the behavior of an individual driver, how an accepted driving practice spreads and whether there is a threshold level of adoption needed for other drivers to adopt a driving practice. Zaidel points out that visible behaviors, such as seat belt usage, speeding, stopping at stop signs, etc., whether desirable or undesirable, are more likely to diffuse quickly than invisible behaviors (for example, DUI).

Conspicuous anti-social behaviors include "cutting up" another driver, making threatening gestures and not signaling are easily copied by other drivers, and bad habits diffuse quickly. Some anti-social behaviors, such as parking on the wrong side of the street spread very quickly. Zaidel asks why it takes longer to convince motorists to roll back the illegal parking habits than it took for the habits to spread, and why illegal parking habits spread quickly, while drinking and driving campaigns need large-scale and prolonged intervention (*45*). Zaidel suggests that the modeling of epidemics and contagious diseases has analogies with traffic behavior. At a simpler level, modeling changes in traffic violations over time may illuminate citizens' views of what is fair and help to explain shifts in the culture of driving.

If these cultural shifts could be better understood, more effective interventions could be devised and aimed at driver sub-groups, for example, young drivers. General beliefs about safety belts, the influence of alcohol on driving, etc., all evolve over time through the "influence of individual driver experiences and learning, expert persuasion, media information, group interaction and collective phenomena such as imitation" (*45*), but what are the mechanisms at work? How do we start and encourage a good "snowball" effect? How do we stop or dissipate an undesirable "snowball"? How do we create a safer traffic environment by improving the "culture of driving" or by changing the "social climate"?

Zaidel believes that shifts in driver culture include changes in observable driving behaviors and changes in a driver's set of related beliefs. The 1998 SARTRE study found, for example, that young drivers' beliefs include having more confidence than older drivers in seat belts (*44*). Among drivers in general, many agreed that seat belts reduce injury, but many appeared to feel that, as they personally were careful drivers, they did not need to wear one (*44*). Zaidel regards understanding driver beliefs and modeling changes as a major challenge, but an approach that will help us to understand and the influence the course of drivers (*45*).

There is a need to understand of the nature of road-use culture and the behavioral and social factors that may influence driver behavior and affect drivers' judgments and opinions about driving and the traffic system. There are about 42,000 fatalities each year in the United States from motor vehicle accidents. About 9,500 fatalities (35%) are intersection-related, about 13,000 fatalities (31%) are speed-related and about 17,000 fatalities (40%) are due to alcohol-related crashes. What role do behavioral issues play in these accidents? How do behavioral issues affect driver responses to signal timing and phasing, channelization, speeding, persuasive messages, running red lights, laws and regulations, enforcement, safety campaigns and many other driving issues? Can we influence and change road culture? How do road-use cultures vary from place to place and over time, and how does this variation manifest itself in the number of accidents on the network?

Few studies provide a quantitative analysis of the role of road culture and behavioral issues in road accidents. The theoretical and methodological difficulties associated with measuring the safety effects of different road cultures are considerable. Researchers tend to follow either a theoretical line of enquiry or a very practical and down-to-earth "what works?" approach. Some approaches emphasize the role of factors that influence the individual in road-use culture and others emphasize the role of factors that influence the group. As research continues, new knowledge will allow future editions of the HSM to provide quantitative information on the relationship between road culture and safety.

At present, studies are available on specific issues such as young and new drivers and graduated driver licensing programs, older drivers, and drivers' responses to various engineering, enforcement, education and legislative measures designed to improve safety.

This section discusses the safety issues and implications of different road-use cultures, and the interventions that affect those cultures in the areas of engineering, enforcement, and education. Road-use culture and the various interventions need to be considered against the background of the legislation and judicial system in operation.

Local road-use culture affects every aspect of road use. Engineering treatments, enforcement, education, legislation and operational management all have to function in the context of the local road-use culture. Transportation agencies and other professionals need to know if and how road users respond to specific safety treatments and safety programs so they can design treatments and programs that are likely to be successful.

Exhibit 7-12: Resources examined to investigate the safety effect of road-use culture

DOCUMENT	DESCRIPTION	COMMENT
(*46*) (Insurance Institute for Highway Safety, "Electronic Stability Control." Status Report, Vol. 40, No. 1, Arlington, Va., Insurance Institute for Highway Safety, (2005))	The Insurance Institute for Highway Safety's press release discuses the Institute's study of states that have changed from secondary to primary laws for seat belts.	Added to synthesis. Little or no quantitative information.
(*47*) (Gains, A., Heydecker, B., Shrewsbury, J., and Robertson, S., "The National Safety Camera Programme: Three Year Evaluation Report." London, United Kingdom, PA Consulting Group, (2004))	The study analyzed the effectiveness of a speed and red lights camera program in the U.K.	Added to synthesis. Little or no quantitative information.
(*48*) (Chaudhary, N. K., Solomon, M. G., and Cosgrove, L. A., "The Relationship Between Perceived Risk of Being Ticketed and Self-Reported Seat Belt Use." Journal of Safety Research, Vol. 35, No. 4, New York, N.Y., Elsevier, (2004) pp. 383-390.)	The study investigated seat belt infraction and the perceived risk of being ticketed (PRT) in relation to laws and enforcement.	Added to synthesis. Little or no quantitative information.
(*49*) (Insurance Institute for Highway Safety, "U.S. Driver Licensing Renewal Procedures for Older Drivers." Arlington, Va., Insurance Institute for Highway Safety, (2004))	The Insurance Institute for Highway Safety tracks state laws on licensing procedures for older drivers.	Added to synthesis. Little or no quantitative information.
(*50*) (Greenberg, M. D., Morral, A. R., and Jain, A. K., "How Can Repeat Drunk Drivers Be Influenced To Change? An Analysis of the Association Between Drunk Driving and DUI Recidivists' Attitudes and Beliefs." Journal of Studies on Alcohol, Vol. 65, No. 4, New Brunswick, N.J., Rutgers Center of Alcohol Studies, (2004) pp. 460-463.)	The project studied the beliefs of people with multiple driving under the influence (DUI) offenses to improve public policy interventions designed to deter or prevent drunk driving.	Added to synthesis. Little or no quantitative information.
(*51*) (Aultman-Hall, L., and Padlo, P., "Factors Affecting Young Driver Safety." JHR 04-298, Rocky Hill, Conn., Connecticut Department of Transportation, (2004))	The study assessed young drivers' crash types and their relevance to GDL restrictions. The study used Connecticut data.	Added to synthesis. Little or no quantitative information.
(*52*) (University of California, "Bringing DUI Home: Reports from the Field on Selected Programs." Traffic Safety Center Online Newsletter, Vol. 1, No. 3, Berkeley, Calif., University of California, (2003))	The study investigated a drinking and driving prevention program in Salinas, Calif. The program used a broad variety of approaches and interventions.	Added to synthesis. Little or no quantitative information.
(*53*) (Agent, K. R., Green, E. R., and Langley, R. E., "Evaluation of Kentucky's "Buckle Up Kentucky: It's The Law & It's Enforced" Campaign." KTC-03-26/KSP1-03-11, Lexington, Ky., Kentucky Transportation Center, (2003))	The report documents the publicity efforts and results of the "Buckle-Up Kentucky" seat belt campaign of 2003.	Added to synthesis. Little or no quantitative information.
(*54*) (Mayhew, D. R. and Simpson, H. M., "Graduated Driver Licensing." TR News, Vol. 229, No. November-December 2003, Washington, D.C., TRB, (2003))	The report traces the development of graduated driver licensing (GDL) programs and discusses studies of the safety effectiveness of GDL programs.	Added to synthesis. Little or no quantitative information.
(*55*) (Neuman, T. R., Pfefer, R., Slack, K. L., Hardy, K. K., Raub, R., Lucke, R., and Wark, R., "NCHRP Report 500 Volume 1: A Guide for Addressing Aggressive-Driving Collisions." Washington, D.C., Transportation Research Board, National Research Council, (2003))	The report discusses aggressive driving and suggests several strategies for addressing the problem of aggressive drivers.	Added to synthesis. Little or no quantitative information.

DOCUMENT	DESCRIPTION	COMMENT
(*6*) (U.S.Department of Transportation, "Considering Safety in the Transportation Planning Process." Washington, D.C., U.S. Department of Transportation, (2002))	The report focuses on incorporating safety into the transportation planning process for the multi-modal transportation system. It provides planners with information and techniques to better understand the role of safety within the transportation planning process.	Added to synthesis. Little or no quantitative information.
(*56*) (Hogue and N.L., "Crash Reduction Due to the Installation of Red Light Cameras: Guidelines for Site Selection." SWUTC/02/473700-00003-4, College Station, Tex., Texas Transportation Institute, (2002))	The study assessed the use of automated enforcement to combat red light violators in the U.S. and elsewhere.	Added to synthesis. Little or no quantitative information.
(*57*) (Fuller, R., "From Theory to Practice: Implications of the Task-Capability Interface Model for Driver Training." London, United Kingdom, Department for Transport, (2000))	The study investigated the causes of crashes from a psychological perspective, especially the problem of determining the conditions under which driver capability falls short of what is required.	Added to synthesis. Little or no quantitative information.
(*58*) (Smith, D. J., "Human Factors and Traffic Crashes." Ames, Iowa, Center for Transportation Research and Education, (2000))	The paper focuses on factors that may cause driver error. Alcohol is a major factor.	Added to synthesis. Little or no quantitative information.
(*59*) (Stuster, J, Coffman, Z, and Warren, D, "Synthesis of Safety Research Related to Speed and Speed Management." FHWA-RD-98-154, Washington, D.C., FHWA, (1998))	The report is a synthesis of research findings on the safety effects of speed, speed limits, enforcement, and engineering measures to manage speed.	Added to synthesis. Little or no quantitative information.
(*60*) (Transportation Research Board, "Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits." Special Report 254, Washington, D.C., National Academy Press, (1998))	The review is a TRB special report that reviews current practice for setting and enforcing speed limits.	Added to synthesis. Little or no quantitative information.
(*44*) (The SARTRE Group, "The Attitude and Behaviour of European Car Drivers to Road Safety." SARTRE 2 Reports, Part 3, Leidschendam, Netherlands, Institute for Road Safety Research (SWOV), (1998) pp. 1-38.)	This study reports on an international survey of European car drivers designed to investigate road and driver behavior and opinions about safety issues including drinking and driving, speeding, seat belt wearing, and possible countermeasures.	Added to synthesis. Little or no quantitative information.
(*61*) (Rogers, P. N., "Specific Deterrent Impact of California's 0.08% Blood Alcohol Concentration Limit and Administrative Per Se License Suspension Laws. Volume 2 of: An Evaluation of the Effectiveness of California's 0.08% Blood Alcohol Concentration Limit and Administrative Per Se License Suspension Laws." CAL-DMV-RSS-97-167;AL9101, Sacramento, Calif., California Department of Motor Vehicles, (1997))	The project evaluated the impact of two (DUI) laws introduced in California in 1990.	Added to synthesis. Little or no quantitative information.
(*62*) (Ontario Injury Prevention Resource Centre, "Best Practice Programs for Injury Prevention." Toronto, Ontario, Canada, Ontario Injury Prevention Resource Centre, (1996))	The study investigated Ontario Ministry of Health priorities for 1992 including prevention of injuries to bicyclists and motor vehicle occupants.	Added to synthesis. Little or no quantitative information.

DOCUMENT	DESCRIPTION	COMMENT
(*45*) (Zaidel, D. M., "A Modeling Perspective on the Culture of Driving." Accident Analysis and Prevention, Vol. 24, No. 6, Great Britain, Pergamon Press Ltd., (1992) pp. 585-597.)	Zaidel discusses the possibility of traffic behavior modeling. He discusses how the individual driver and the collective of drivers interact, and how the culture of driving changes.	Added to introduction to section. Little or no quantitative information.

7.6.1. Engineering Treatments

7.6.1.1. Network-wide Consistency

The consistency of engineering measures at the network wide level as well as at each individual location is likely to affect the driving habits and road-use culture of local users who come to expect certain procedures and to act accordingly. Examples include all-red phases at traffic signals, right-turn-on-red policy, the use of left-turn arrows or flashing lights at traffic signals, and policies regarding yielding at intersections and roundabouts. When the approach adopted is not consistent across the jurisdiction, safety deterioration may take place. This effect is shown when unfamiliar drivers encounter quite different rules of the road when traveling in a foreign country. No resources that study the impact of network-wide consistency were found.

7.6.1.2. Mitigate aggressive driving

Many issues relating to aggressive driving can be linked to problems with engineering and infrastructure. Driver frustration may arise, for example from delays. This frustration may lead to aggression and an increased likelihood of accidents.

Neuman et al.'s view is that suitable engineering measures could be used to prevent aggression from occurring (*55*). The authors discuss the elements that can lead to frustration including engineering issues such as uncoordinated traffic signals and a lack of accurate information regarding causes of traffic delays, but Neuman et al. reported that "no program has been found" that includes corrective engineering actions ((*55*), pg V-17).

While there have been reports of dealing with aggressive driving and reducing the number of crashes, Neuman et al. point out that the success may be due to the use of law enforcement rather than to an understanding of aggressive driving. "No effort has addressed the treatment of engineering elements as a means of mitigating aggressive driving, even though traffic safety professionals recognize that the driving environment plays a role in driver behavior" (*55*).

Neuman et al. propose to reduce aggressive driving by improving the driving environment (*55*). The strategy is two-pronged. The first step aims to mitigate problem elements in the driving environment, but needs further research as "programs related to aggressive driving are too new to have been adequately evaluated" ((*55*), page V-4). Multi-disciplinary teams of safety experts will be needed to correct aggressive driving and to explore the frustration-aggression approach which remains experimental. The frustration that occurs, for example, on roads with inappropriate speed limits, encouraging drivers to disregard the posted limit, may continue to be a problem unless the speed limit is made more appropriate. Further examples are poorly coordinated traffic signals (which encourage red light running), inadequate exit ramps (which encourage driving on the shoulder or median), inadequate exit ramps (which encourage improper merging), inadequate left-turn lanes, and unclear traffic controls in work zones (*55*). In 2002, no programs were known to be attempting to improve the driving environment and mitigate aggressive driving by minimizing these "triggers" of aggressive driving (*55*).

The second prong of the strategy to improve the driving environment aims to reduce non-recurring delays and provide better information about these delays. Motorists want accurate and timely information. Many information systems are available, but it is necessary to know which ones work and which ones are best for managing incidents and keeping traffic moving. Neuman et al. found no research into aggressive driving and areas of non-recurring delay or regular congestion (*55*).

7.6.2. Enforcement Interventions

The discussion of enforcement is divided into:

- Speed enforcement (mobile patrol vehicles, stationary patrol vehicles, radar, etc);
- Enforcement to reduce red-light running;
- Enforcement to increase seat belt and helmet use; and
- Enforcement to reduce driving under the influence.

7.6.2.1. Enforcement to reduce speeding

Speed issues are discussed in Chapter 2. Speed is believed to contribute to 12% of all crashes and 30% of fatal crashes (Bowie and Walz, 1994 cited by (*59*)).

In a driving culture, the social environment and associated social behaviors create norms. One of the most important norms is acceptable driving speed. Aware of the norm, a driver who notices that a driver ahead is slowing down will respond in an appropriate way. Most people conform to the behavior expected, but some drivers fall short of what is required. Drivers who do not conform to society's rules and norms for driving behavior, or who are driving in unfamiliar surroundings where the prevailing road-use culture differs from their own, may be more likely to have an accident than drivers who are familiar with the local road-use culture and conform to it.

Drivers assess the road's characteristics (curvature, number of lanes, grade, length of grade, number of lanes, surface condition, sight distance, and maintenance condition, among others), the adjacent land use, the number of access points and the roadway surroundings (such as tall objects close to the road) to choose the driving speed they consider to be appropriate (*59*). The weather also influences most drivers although many drivers fail to reduce their speed on wet roads (Lamm et al. 1990, cited by (*59*)).

The speed choices ultimately made by drivers often exceed the posted limits. A 1990 study of low and moderate speed roads in four States found that 70%of drivers were exceeding the speed limit (Harkey et al. 1990, cited by (*59*). Although "there is evidence that crash risk is lowest near the average speed of traffic" ((*59*), pg 14), the human preference for exceeding the speed limit is an important safety issue because the risk "increases exponentially for motorists traveling much faster" ((*59*), pg 14), and the speed of the vehicle on impact greatly affects the severity of any crash that occurs.

Unfortunately, most drivers, when surveyed, have been found to underestimate their driving speed, especially when driving fairly fast or fast. After a high-speed period, drivers who slow down typically perceive their new speed as lower than it actually is (Schmidt and Tiffin, 1969; Mathews, 1978 cited by (*59*)). In addition, perceptual limitations lead to drivers failing to respond appropriately to curvature (Shinar, 1977 cited by (*59*)). Since drivers tend to drive at the speed that they find acceptable and safe despite posted speed limits, little or no effect on speed has been found for low and moderate speed roads where speed limits were changed (raised or lowered) (*59*). In the case of freeways, higher speeds and more injury crashes have occurred after speed limits were raised. This is important because "for every 1 mi/h change in speed, the number of injury crashes increases 5 percent" (3%for every 1 km/h) (Finch et al. 1994, cited by (*59*)). The net safety effect of speed limits and changes in speed limits across the network is not known.

It is clear that speed limits are necessary, but the system wide implications of speed limits and driver responses and the various options for enforcement interventions need research to understand their effect on the road-use culture.

Some enforcement approaches are known to have spillover effects across the network. For example, speed cameras installed at local intersections may affect behavior at intersections not equipped with the cameras. The publicity and public interest accompanying installation of the cameras may lead to a "generalized change in driver behavior at intersections with and without cameras" ((*46*), pg 6). Some enforcement approaches also have "time halo" effects in which the effect of the enforcement remains after the enforcement has been withdrawn.

Eight speed enforcement interventions are discussed below.

Discussion: Mobile patrol vehicles

A 1986 study found that the greatest compliance with speed limits occurred close to mobile patrol vehicles. Compliance decreased with distance from the patrol vehicles (Shinar and Stiebel 1986, cited by (*59*)). In Illinois, when the overhead lights were removed from patrol cars, these vehicles ticketed 25% more motorists than before, suggesting that their visible presence had been a deterrent to speeding for many drivers (Raub 1985, cited by (*59*)).

Benekohal et al. (1992) found that the presence of mobile patrol vehicles reduced the average speeds of cars and trucks in a highway construction zone. The time halo effect lasted an hour after the vehicles left the site (Benekohal et al. 1992, cited by (*59*)). Vaa's study of very intensive daily police presence found a time halo effect of vehicle speed reductions that lasted up to 8 weeks (Vaa 1997, cited by (*59*)).

Discussion: Stationary patrol vehicles

Stationary patrol vehicle enforcement led to "a pronounced decrease in average traffic speed." The vehicle had to be present for five days for vehicle speeds to be reduced even after the vehicle had gone (Hauer et al. 1982, cited by (*59*)). A 1986 study investigated the effect of a stationary patrol vehicle positioned on an urban street. The decrease in speed was "measurable" and the number of drivers exceeding the speed limit dropped by two-thirds (Armour 1986, cited by (*59*)).

Discussion: Aerial enforcement

Aerial enforcement has been found to reduce highway speeds. In Australia, vehicle crashes were reduced by 22% (Kearns and Webster 1988, cited by (*59*)). An earlier Australian study found that when aerial enforcement came to an end, the number of car drivers and truck drivers exceeding the speed limit increased by 6% (Saunders 1979, cited by (*59*)). In New York, aerial enforcement was used successfully to apprehend drivers who used radar detectors and CB radio to avoid being caught (Blackburn, Moran and Glauz 1989, cited by (*59*)).

Discussion: Radar and laser speed monitoring equipment

Laser guns have been used as an alternative to radar, successfully apprehending drivers with radar detection in their cars. Those caught with radar detectors tended to be the drivers "traveling at the most extreme speeds" (Teed and Lund 1991, cited by (*59*)).

Discussion: Automated enforcement

Automated enforcement systems use video or photographic identification in conjunction with radar or lasers to detect speeding drivers and automatically record the vehicle registrations.

In Melbourne, Australia, there was a statistically significantly reduction in injury crashes within 1 km of the speed camera during "high alcohol hours" on arterial roads. Mean speeds were not reduced, but the number of drivers who exceeded the speed limit by more than 15 km/h decreased (details not given) (Rogerson et al. 1994, cited by (*59*).

Elvik and Vaa (*64*) found that automated enforcement reduced injury crashes at sites with high accident rates by 26%. At other sites, the reduction was only 5%. Elvik and Vaa also undertook a meta analysis using data from several countries and found that automated enforcement brought about a 17% reduction in injury crashes. The study by Elvik and Vaa (*64*) was rated High and a MCF of 1.2 was used to adjust the standard errors.

The "National Safety Camera Programme" in the United Kingdom was introduced to reduce speed and red light running. Gains et al. reported on the effectiveness of the system from 2000 to 2003 (examining 24 areas operating the program for at least a year) (*47*). The program was well supported by the public. At fixed camera sites, Gains et al. found that vehicle speed dropped by about 7%. Excessive speeding (i.e. traveling at 15 mph more than the speed limit) dropped by 80% at fixed camera sites. Mobile camera sites were also effective, but the percentages were considerably lower than at fixed camera sites. The report concludes that the safety camera program to reduce road accidents "is extremely successful at reducing speed, accidents, casualties and saving lives" ((*47*), pg 62).

Chen et al., 2002, evaluated the safety impacts of mobile photo radar enforcement on a 22 km Vancouver Island segment of Highway 17 (Pat Bay Highway) in British Columbia (*65*). The empirical Bayes method was used to control for regression to the mean and time effects. The before and after periods were limited: 2 years each. Mean speed reduced by about 2 km/h (3% reduction) and standard deviation decreased by about 0.5 km/h (6% reduction). Crashes reduced by about 16% in the corridor as a whole. An MCF of 1.8 was used to adjust the standard errors from this study.

Mountain et al., 2004, examined the impact of 62 fixed speed camera sites on roads with severe speeding problems throughout the United Kingdom (*66*). Data were collected for upto 2 km centered on the camera site. The empirical Bayesian method was used for the evaluation. Considering a 500 m monitoring length, personal injury crashes decreased by about 25%, out of which 20% was attributed to the impact of cameras on speed (and possibly other aspects of speed behavior), and about 5% of the reduction attributed to diversion of traffic to other routes. Consider a 1 km monitoring length, the reduction in injury crashes was 25%. An MCF of 1.2 was used to adjust the standard errors from this study.

Goldenbeld and van Schagen (2005) studied the impact of mobile, inconspicuous speed cameras on rural roads in the Friesland Province of Netherlands (*67*). Treatment was directed at 80 and 100 km/h single carriageway roads with high injury crashes. For evaluating the effects on safety, the experimental group included 28 speed camera enforced road sections (average length of about 4 km), and the comparison group included all other rural roads in the province of Friesland, approximately 5,200 km total length. Injury crashes reduced by 21% following the introduction of the automated enforcement. An MCF of 2.2 was used to adjust the standard errors from this study.

Christie et al., (2005), examined the safety impacts of mobile speed cameras in South Wales, United Kingdom (*68*). There were 101 mobile speed camera studies throughout the region at rural and urban locations. The majority of the sites were on 30 mph speed limit roads. Matched control sites were selected from Gwent, a neighboring police enforcement district, with only one mobile and no static cameras. Within 500 m on either side of the camera sites, there was a 51% reduction in injury crashes. An MCF of 2.2 was used to adjust the standard errors from this study.

The Australian Road Research Board (ARRB) evaluated the safety impact of 28 unattended fixed speed cameras in New South Wales, Australia (*69*). Cameras had primarily been installed in locations with high crash rates or high severity crashes that subsequently underwent speed analysis, site review, and consideration of other potential safety treatments. For the before after analysis, camera sites were matched with controls based on speed limit, number of lanes, and roadway cross section (divided/undivided). At the camera segments, there was about a 23% reduction in fatal and injury crashes. An MCF of 2.2 was used to adjust the standard errors from this study.

Exhibit 7-13 shows the AMFs and their standard errors from studies that evaluated the effect of automated enforcement on safety. Based on the results of these studies, a combined AMF and standard error was recommended for inclusion in the HSM.

Exhibit 7-13: Safety Effects of Automated Enforcement

Author, date	**Treatment/ Element**	**Setting**	**Road type & volume**	**Accident type & severity**	**Index of Effectiveness, $t_{adjusted}$**	**Estimate of Std. Error, s**
Elvik and Vaa, 2004	Automated Enforcement Mobile and Fixed Cameras	Not specified.	Not specified.	Injury Crashes	0.830	0.009
Chen et al., 2002	Automated Enforcement Mobile Cameras	Not specified.	Not specified.	Injury Crashes	0.840	0.108
Mountain et al., 2004	Automated Enforcement Fixed Cameras	Not specified.	Not specified.	Injury Crashes	0.810	0.072
Goldenbeld and Schagen, 2005	Automated Enforcement Mobile Cameras	Not specified.	Not specified.	Injury Crashes	0.790	0.163
Christie et al., 2005	Automated Enforcement Mobile Cameras	Not specified.	Not specified.	Injury Crashes	0.490	0.084

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
ARRB, 2005	Automated Enforcement Fixed Cameras	Not specified.	Not specified.	Injury Crashes	0.772	0.176
Combined	**Automated Enforcement Mobile and Fixed Cameras**	**Not specified.**	**Not specified.**	**Injury Crashes**	**0.826**	**0.009**

Discussion: Drone radar

Drone radar (unattended radar transmitters) was tested by Freedman, Teed and Migletz (1993) in a construction zone. The results showed only a slight reduction in average vehicle speed, but there was a 30 to 50% decrease in the number of drivers who exceeded the speed limit by more than ten miles per hour (Freedman, Teed and Migletz 1993, cited by (*59*)). Similar findings were documented by Streff, et al. (Streff et al. 1995, cited by (*59*)).

Discussion: Speed feedback indicators

Variable message displays can be used to display the speed of a vehicle to drivers to increase drivers' awareness of their speeds and to encourage drivers to slow down. In Casey and Lund's 1990 study, speeds were decreased while the indicator was installed, but not after it was removed (Casey and Lund 1990, cited by (*59*)). Speed reduction also ceased after speed feedback trailers were removed from residential sites in Texas. While the trailers were operating, the speed reductions were 2 to 3 mph (3 to 5 km/h) (Perrillo 1997, cited by (*59*)). A much earlier study (1976) found no significant effect on traffic speeds from variable message displays (Dart and Hunter 1976, cited by (*59*)).

Based on the work by cited in Elvik and Vaa (*64*), the AMF from Exhibit 7-14 was recommended for use in the Highway Safety Manual for the safety effect of changeable speed warning signs. An MCF of 1.8 was used to adjust the standard errors from this study.

Exhibit 7-14: Safety Effects of Changeable Speed Warning Signs

Author, date	Treatment/ Element	Setting	Road type & volume	Accident type & severity	Index of Effectiveness, $t_{adjusted}$	Estimate of Std. Error, s
Elvik and Vaa, 2004	Changeable speed warning signs	Not specified.	Not specified.	All types	0.54	0.17

Discussion: Traffic enforcement notification signs

Stuster investigated portable traffic enforcement warning signs in Huntington Beach, California. These signs warn the public that they are entering (or leaving) an area where thorough traffic enforcement is taking place. Stuster found a 17% reduction in injury crashes (Stuster 1995, cited by (*59*)). Regression-to-the-mean, however, may explain much of this effect as the warning signs and additional traffic enforcement are directed towards locations considered to be particularly hazardous.

Summary

Speed limits need to be largely self-enforcing. It is clear from the many studies reviewed that the main problem with speed enforcement is that the effectiveness of enforcement measures is usually short-term and limited to the immediate vicinity of the enforcement. Most enforcement interventions appear to have little effect in modifying road-use culture. If drivers believe that speed limits are unreasonable, inappropriate or inconsistently applied to the network, it is very unlikely that temporary enforcement measures can bring about permanent speed reductions. Even if enforcement is strictly applied to certain roads, speeding may simply migrate to other roads.

"The issue of appropriate driving speeds … will persist as long as there are individual drivers making choices about risk and time efficiency. Ultimately, decisions about appropriate speed limits depend on judgments about society's tolerance for risk, valuation of time, and willingness to police itself" ((*60*), pg 14).

7.6.2.2. Enforcement to reduce red-light running

Red-light camera (RLC) systems have been used in the United States for a few years. According to Hogue and Dudek, red light running led to 106,000 crashes, 89,000 injuries and about 1,036 deaths in the United States in the year 2000 (*56*). No studies have been found documenting whether the number of drivers running red lights is increasing or decreasing, and no comments have been found regarding the type of driver who is most likely to run red lights.

The use of automated enforcement offers considerable savings compared with the expense involved in having police surveillance at intersections followed by the police having to chase and stop vehicles that have run a red light. RLC systems are usually installed at intersections with particularly high accident rates. Chapter 4 provides some information on the safety effectiveness cameras installed at signalized intersections for target accidents.

As discussed in Section 7.6.2.1, Gains et al. reported on the effectiveness of the "National Safety Camera Programme" in the United Kingdom (*47*). The program was well supported by the public, but there are no well-documented comments on any changes in road-use culture after the installation of the cameras.

7.6.2.3. Enforcement to reduce driving under the influence

General beliefs and attitudes towards drinking and driving vary and are not well documented. The 1998 SARTRE study found that the perceived risk of being breathalyzed on a journey is low across Europe, but that attitudes in Northern European differ from those in Southern Europe (*44*). Drivers in Northern European countries tend to support strict drinking and driving laws and to reject any personal freedom in drinking and driving. Southern European drivers, however, underestimate alcohol risks for adult drivers. They have a far more lenient approach towards adult drivers who, they feel, should in most cases be able to police themselves. Southern European drivers see drinking and driving as a problem of young drivers who should be completely forbidden to drink and drive.

Greenberg et al. recently interviewed 273 people with multiple driving under the influence (DUI) offenses to establish how these offenders' beliefs were related to their impaired driving (*50*). The study was intended to help to focus public policy interventions designed to deter or prevent drunk driving. Greenberg et al. concluded that behavioral controls have the best prospects for reducing drunk driving

(*50*). Behavioral controls included internal behavior controls such as moral beliefs concerning alcohol-impaired driving, and external behavioral controls such as the offenders' perceptions of accidents and criminal punishment. Social controls (peer group pressure) appeared to be less important.

It is clear that alcohol has a major effect on driver error and that DUI is a major problem. Smith believes that "the number of alcohol related fatalities may be underestimated" and that it is likely that "some drivers become impaired well before the blood alcohol content (BAC) of 0.10 is reached" (*58*). Fuller points out that young, male drivers, alcohol, and high speed are a lethal combination: "these factors are associated with 40% of all loss-of-control fatal crashes involving young male drivers aged 18 to 21 years" (Laapotti and Keskinen cited by (*57*)).

Many approaches have been tried in the attempt to reduce DUI. The approaches include classes for juvenile DUI offenders, alcohol abuse treatment as an alternative to license suspensions, lowering the legal blood alcohol limit to 0.05, introducing random breath testing, and bar staff training. These particular approaches were assessed by the Ontario Ministry of Health in 1992, but there appeared to be no clear pattern of driver response (*62*). Some drivers were frequent violators and appeared to need special attention and policies (*62*).

Rogers' study emphasized the importance of punishment (*61*). Rogers' study evaluated two DUI laws introduced in California in 1990. One law reduced the permitted blood alcohol concentration (BAC) limit to 0.08 and the other law imposed a pre-conviction license suspension on arrested DUI offenders. These laws were "highly effective in reducing subsequent accidents and recidivism among DUI offenders" (*61*).

The University of California's Berkeley Traffic Safety Center concluded that "drinking and driving prevention seems to be most successful when it engages a broad variety of programs and interventions" (*52*). The authors investigated a program that included highly publicized sobriety checkpoints (which Smith regards as one of the most useful measures for deterring drunk driving (*58*)), responsible beverage service training, underage drinking controls, limits on alcohol availability, and media advocacy. The program was introduced in Salinas, California where it "succeeded not only in mobilizing the community, but also in reducing traffic injuries and impaired driving over a sustained period of time. Traffic crashes, injuries, and drinking and driving rates, all decreased as a result of the project" (*52*). The researchers commented that programs that concentrated only on sobriety check points succeeded in achieving a "decrease in crash numbers" and an increase in DUI arrests over the short term, but were not successful over the longer term.

These results of the studies discussed indicate that the culture of drinking and driving can be modified, but that change requires concentrated legislation and enforcement efforts and appropriate community programs to achieve long term and sustainable results.

7.6.2.4. Enforcement to increase seat belt and helmet use

In 2004, every state except New Hampshire had a seat belt use law, but most states had secondary seat belt use laws rather than primary seat belt use laws. The National Highway Traffic Safety Administration's 2004 survey found that seat belt use averaged "84 percent in primary states compared with 73 percent in secondary states" (*46*). The Insurance Institute for Highway Safety (IIHS) has recently conducted the first study of the effect of changing from secondary belt use law to primary law on accident fatalities. The IIHS examined driver fatalities in 10 jurisdictions where secondary laws were amended to primary (California, the District of Columbia, Georgia, Indiana, Louisiana, Maryland, Michigan, New Jersey, Oklahoma, and Washington). The data were from 1989 to 2003. The change in laws was usually combined with enhanced enforcement as many states participated in special 'Click It or Ticket' seat belt enforcement campaigns. The Institute found that the enforcement campaigns and change to primary laws increased seat belt usage, and calculated that "when states strengthen their laws from secondary enforcement to primary, driver death rates decline by an estimated 7 percent" (*46*).

In the same press release, the IIHS points out that "65 percent of those killed riding on motorcycles weren't wearing helmets" and that "In states with universal helmet requirements, 80 percent of the motorcyclists were helmeted, compared with 14 percent in states without such laws" (*46*).

Chaudhary et al. examined the perceived risk of being ticketed for not wearing a seat belt (*48*). Chaudhary et al. recommended that existing laws should be strengthened "to create a higher perception of being ticketed" and that selective traffic enforcement programs to enforce of existing laws could increase safety belt use (*48*).

Agent et al. investigated Kentucky's 2003 "Buckle up Kentucky: It's the law and it's enforced" campaign (*53*). The campaign started three weeks before Memorial Day 2003. The enforcement period was one week before and one week after Memorial Day 2003. Agent et al. found that there was a drop in injuries during the two-week enforcement period. The authors recommended that the law in Kentucky should be changed from secondary to primary enforcement and that the public must be made aware that the law is being enforced (*53*).

The studies above indicate that the adoption of primary seat belt laws will increase the use of seat belts and effectively modify road-use culture. This finding is supported by the 1998 SARTRE study in Europe that found that for seat belt usage, there were few voluntary adopters (*44*). People were more likely to wear seat belts after legislation was introduced and the law was necessary to help to create the critical threshold after which adoption was widespread.

7.6.3. Education Programs

Typical education issues and initiatives include:

- Public education campaigns;
- Young drivers and graduated driver licensing programs; and
- Older drivers and retesting older drivers.

7.6.3.1. Public education campaigns

Most enforcement efforts include public information, warnings, or educational campaigns. Maekinen and Oei (1994) "stress that publicity and warning signs contribute significantly to the effectiveness of the technology" used in enforcement Maekinen and Oei (1994) (cited by (*59*)). "Traffic safety programs that include highly visible public information and education (PI&E) campaigns that accompany law enforcement efforts have proven to both increase positive public impressions toward police activities and result in safer driving habits" (*59*). Regarding positive public impressions, a program in Boise, Idaho, was able to show the police as genuine in their wish to use enforcement to promote safety rather than to stop motorists and impose fines (*59*).

Stuster et al. found that the most effective programs comprise integrated PI&E and law enforcement (*59*). None of the PI&E campaigns that they reviewed resulted in a "significant reduction in speed, speeding, crashes, or crash severity" unless the campaign was "closely tied to an enforcement or engineering program" (*59*). "General assessment of public information programs has shown them to have limited effect on actual behavior except when they are paired with enforcement" ((*55*), page V-11).

Neuman et al. emphasize the importance of using multimedia that are carefully planned, professionally produced and expensive, but "while some agencies have reported successful public information campaigns and linked those campaigns to targeted enforcement, there is little published evidence of [the] effectiveness" of PI&E campaigns and "assessing the effectiveness of a large scale public information campaign is almost impossible". It may only be possible to test for public awareness of the problem and knowledge of the campaign's message. Testing needs to determine drivers' exposure to the message and their response to the message (*55*).

7.6.3.2. Young drivers and Graduated Driver Licensing programs

Graduated driver licensing (GDL) programs were developed because novice drivers have an increased risk of crashes. Teenagers are more likely to be involved in deadly crashes than are most other age groups (*6*). Teenage drivers are three times more likely to be in a fatal traffic crash than are other drivers (NHTSA, 1998 cited by (*51*)).

Aultman-Hall and Padlo used 1997 to 2001 crash reports for drivers aged 16 to 20 years in Connecticut. Their study investigated the relative propensity of young drivers to cause a traffic crash ((*51*), pg 22):

- At night
- On freeways vs. non-freeways
- Driving with passengers (by number and age of passengers).

The results confirmed research that has shown that "young drivers, especially young males and those who are 16 and 17 years old, are more likely to cause both single and two vehicle traffic crashes. The risk is great enough to suggest that this group of drivers should be subject to measures that minimize their exposure, especially in known risky circumstances like nighttime and on freeways." (*51*)

Young drivers' risk is increased due to their age and lack of experience as drivers. Fuller noted that over-representation of young drivers in crashes "appears to be universal" ((*57*), pg 8) despite a wide variety of driver training approaches across Europe. In particular, young male drivers may have a risky life style and they typically over-estimate their competence. They also drive more at night. These factors are transferred to driving and result in higher crash rates.

The immaturity of young drivers gives them an "optimism bias" (Dejoy, 1989 cited by (*51*)). Young teenage drivers are more likely to drink alcohol and drive (NHTSA, 2000 cited by (*51*)) and less likely to wear seat belts (NHTSA, 1998 cited by (*51*). As young drivers mature in age, however, they are less prone to risk-taking life styles and their risk of accidents is reduced.

Recent research "suggests that increased driving experience is somewhat more important than increased age in reducing collisions among young novices" (*54*). Unfortunately, young drivers are at risk while getting the experience they need.

GDL is intended to "encourage new drivers to gain driving experience under conditions that minimize exposure to risk" and to ensure that new drivers are exposed to more demanding driving situations only when they have enough experience (*54*). GDL takes lifestyle factors into account by including restrictions such as zero blood alcohol, not driving on high speed highways, not driving at night, and limitations on the number and age of passengers.

The exact restrictions and progression of GDL programs vary among jurisdictions. GDL was first introduced in New Zealand in 1987. In North America, California and Maryland were the first states to introduce some elements of GDL. Florida introduced a GDL program in 1996. By 2003, 47 states and ten Canadian province and territories had full or partial GDL programs.

Mayhew and Simpson reviewed evaluations of the safety of GDL programs and found that “Research has demonstrated that graduated licensing is an effective public safety measure – all program evaluations published to date have reported safety benefits” with “overall reductions in crashes of 4 to 60 percent” in the United States, Canada and New Zealand (Simpson 2003, cited by (*54*), pg 5). The variation in results may be due to differences in the programs (for example various restrictions applied to carrying teenage passengers or driving at night), differences in the study methodology, and to differences in the age groups studied. Long-term studies “have found sustained and significant reductions of 7 percent” (Langley et al. 1996, cited by (*54*), pg 6).

Mayhew and Simpson noted that GDL enjoys strong support from parents and teenagers (*54*). This support is necessary for GDL to be successful as parents must help by enforcing the restrictions and by ensuring that new drivers get practice.

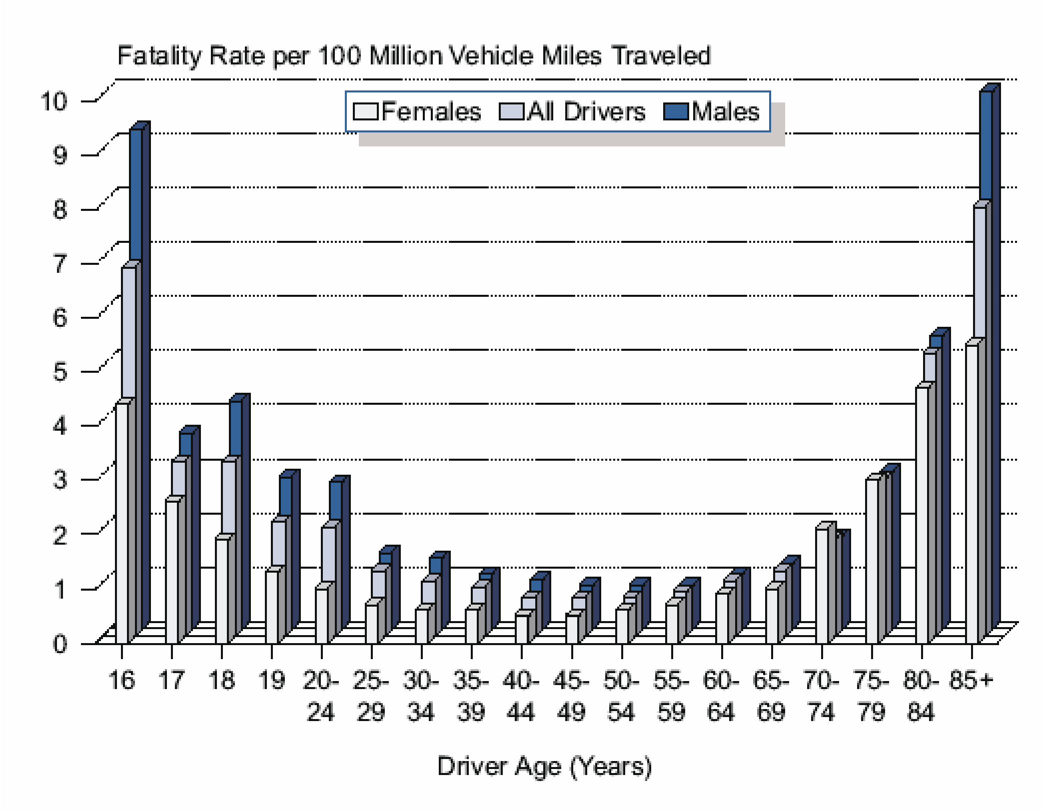
Research should be conducted into how GDL programs can be further improved and how driver education for young people can be extended to go well beyond basic knowledge and skills. Research into driver education for young people might include investigating the effectiveness of driver education programs, the role of social influences among young people, and how best to explain risky driving behaviors, driving as a dangerous activity, situations where driving task demands may exceed capability, and the problem of young drivers’ actual skills versus their perceived skills.

It is believed that GDL programs will modify road-use culture and the approach of new drivers in our communities.

7.6.3.3. Older drivers and retesting older drivers

There is great variability in the way drivers’ abilities decline with age and how this affects the driving skills of the elderly. “There were 18.5 million older licensed drivers in 1999, a 39 percent increase from the number in 1989. In contrast, the total number of licensed drivers increased by only 13 percent from 1989 to 1999” (*63*). By 2030, there will be approximately 70 million older adults, more than twice the number in 1997. Older drivers, along with young drivers, have more accidents per miles driven than any other age group, as shown in Exhibit 7-15.

Exhibit 7-15: Driver fatality rates by age and sex, 1996 (63)



Special renewal procedures for older drivers (in addition to normal renewal procedures) are designed to ensure that older adults meet license requirements (*49*). When drivers reach the age of 65 or 70, most states have shortened renewal cycles and the requirement that older drivers must renew their licenses in person rather than remotely. Older drivers whose capabilities are in doubt may be required to undergo physical or mental examinations. They may also have to retake the standard licensing tests (vision, written, and road tests). Certain restrictions may be applied. These restrictions might include nighttime driving or installing additional mirrors.

The road-use culture of older drivers will be a critical issue in years to come. Communities will need to revisit the infrastructure to accommodate the growing proportion of these road users.

7.6.4. Summary

Motor vehicle crashes are the leading cause of death for Americans. If crashes are to be reduced, it will be necessary to have a much better understanding of driver culture than is presently available. This understanding will help us to design treatments and interventions that are likely to be successful in changing driving behavior and increasing safety, and will also help us to create appropriate safety campaigns and enforcement procedures. Studies suggest that it is particularly difficult to change the road-use culture regarding the choice of driving speed and observation of speed limits, but various levels of progress have been made changing the road-use culture regarding, for example, DUI and seat belt usage. Graduated driver licensing programs and special consideration and testing of older drivers are helping to allow for the special problems of these two groups with the aim of reducing their accident rates.

Studies show that enforcement has a vital role in changing driver behavior, if only in the short term. It should be mentioned that if enforcement is to succeed in reducing undesirable and dangerous driving practices and if enforcement is to have a chance of bringing about a change in road-use culture, it is essential that the supporting traffic laws are sound and well enforced throughout the network. If traffic laws are not enforced, the perceived risk of being apprehended for a traffic violation will be low. If enforcement actions are few and far between, motorists will take advantage of their apparent freedom to speed, drive inconsiderately, run red lights, etc. and will not change their driving habits.

Good enforcement requires public support for what is being enforced. It also requires resources to maintain and, where necessary, increase the law enforcement presence. Automated enforcement (for speed and red-light-running enforcement) with the appropriate enabling legislation offers the potential for important savings.

Enforcement cannot succeed without a supportive administrative and court system. When a ticket is issued, there must be an efficient system that tracks and manages the process of collecting the fine or forwarding the offender to the courts. The police will not aggressively pursue traffic infringements if they know the fines will not be collected or that the courts will not prosecute offenders. There must be consistent treatment of convictions and penalties and as few loopholes as possible.

The public will not take enforcement seriously if they know that the system does not work and that there is a good chance of avoiding conviction. Where driving habits are entrenched and hard to change, it may be necessary for the courts to have the authority to impose strong penalties that convey the message that attitudes and behavior need to change and that aggressive, unsafe driving will not be tolerated.

7.7. Transitions between Highway Facility Types [Future Edition]

In future editions of the HSM, this section may discuss transitions between highway facility types and safety, from a road network perspective. Research from Chapter 5 may be of interest in this section. Potential resources were not identified for this section.

7.8. Security (against Crime) and Safety [Future Edition]

In future editions of the HSM, this section may discuss engineering treatments to increase the security of road users, particularly bicyclists and pedestrians, against crime. For example, overpasses and underpasses are often not utilized at night due to security concerns. Potential resources were not identified for this section.

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