Safety Evaluation of Increasing Retroreflectivity of STOP Signs

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FOREWORD

The goal of this research was to evaluate and estimate the safety effectiveness of increasing retroreflectivity of STOP signs as one of the strategies in the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), Phase I.

The ELCSI-PFS provides Crash Reduction Factor (CRF) and economic analysis for the targeted safety strategies where possible. The estimate of effectiveness for increasing retroreflectivity of STOP signs was determined by conducting scientifically rigorous before-after evaluations at sites where this strategy was implemented in the United States.

This safety improvement and all other targeted strategies in the ELCSI-PFS are identified as low-cost strategies in the *NCHRP Report 500* guidebooks. Participating States in the ELCSI-PFS are Arizona, California, Connecticut, Florida, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Massachusetts, Minnesota, Mississippi, Montana, New York, North Carolina, North Dakota, Oklahoma, Pennsylvania, South Carolina, South Dakota, Tennessee, Texas, Utah, and Virginia.

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16. Abstract
The Federal Highway Administration (FHWA) organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. One of the strategies chosen to be evaluated for this study was STOP signs with increased retroreflectivity. This strategy is intended to reduce the frequency of crashes related to driver unawareness of stop control at unsignalized intersections.

Geometric, traffic, and crash data were obtained at unsignalized intersections for 231 sites in Connecticut and 108 sites in South Carolina. In each case, the strategy was implemented as a blanket application of STOP signs with increased retroreflectivity. Empirical Bayes (EB) methods were incorporated in a before-after analysis to determine the safety effectiveness of increasing the sign retroreflectivity. There was a statistically significant reduction in rear-end crashes in South Carolina. Based on the results of the disaggregate analysis, reductions in crashes were found at three-legged intersections and at intersections with low approach volumes. The analysis also indicated a slight reduction in nighttime- and injury-related crashes in Connecticut and South Carolina, but the results were not statistically significant. It was determined that a sample size much larger than that available would be needed to detect a significant effect in these types of crashes. Given the very low cost of installing STOP signs with increased retroreflectivity, even with conservative assumptions, only a very modest reduction in crashes is needed to justify their use. Therefore, this strategy has the potential to reduce crashes cost-effectively, particularly at lower volume intersections.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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ABBREVIATIONS AND SYMBOLS

Abbreviations

A	Injury, incapacitating
AADT	Average annual daily traffic
ADT	Average daily traffic
AASHTO	American Association of State Highway Transportation Officials
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
B	Injury, nonincapacitating
C	Possible injury
ChiSq	Chi-Squared
ConnDOT	Connecticut Department of Transportation
DF	Degrees of freedom
EB	Empirical Bayes
FHWA	Federal Highway Administration
ft	Feet
HPMS	Highway Performance Monitoring System
KABCO	Scale used to represent injury severity in crash reporting
K	Fatality
mi	Miles
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
O	Property damage only
Pr	Probability
SCDOT	South Carolina Department of Transportation
SPF	Safety performance functions
Stddev	Standard deviation
TRB	Transportation Research Board
UCONN	University of Connecticut
Var	Variance

Symbols

α	Greek letter Alpha
β	Greek letter Beta
Δ	Greel letter Delta
λ	Greek letter Lamda
π	Greek letter Pi
θ	Greek letter Theta

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. The purpose of the FHWA Low-Cost Safety Improvements Pooled Fund Study is to evaluate the safety effectiveness of several of the low-cost strategies through scientifically rigorous crash-based studies. One of the strategies chosen to be evaluated for this study was the implementation of STOP signs with higher retroreflectivity. This strategy is intended to reduce the frequency of crashes related to driver unawareness of stop control at unsignalized intersections. The safety effectiveness of this strategy had not previously been thoroughly documented and this study is an attempt to provide an evaluation through scientifically rigorous procedures.

Geometric, traffic, and crash data were obtained at unsignalized intersections for 231 sites in Connecticut and 108 sites in South Carolina. In each case, the strategy was implemented as a blanket application of STOP signs with increased retroreflectivity. Empirical Bayes (EB) methods were incorporated in a before-after analysis to determine the safety effectiveness of increasing the sign retroreflectivity. For rear-end crashes, there was a statistically significant reduction in crashes in South Carolina. Based on the results of the disaggregate analysis, reductions in crashes were found at three-legged intersections and at intersections with low approach volumes. Installations at three-legged intersections (indiscriminate of urban/rural factor) and three-legged urban intersections in South Carolina were found to have a statistically significant reduction in crashes. In Connecticut, a statistically significant reduction in crashes was found for three-legged rural intersections. The disaggregate analysis also showed that the strategy is more effective at lower volumes for the minor approach. A statistically significant reduction in crashes was found at intersections with approaching volumes of less than 1,200 annual average daily traffic (AADT) in South Carolina and less than 1,000 AADT in Connecticut. The analysis indicated a slight reduction in nighttime- and injury-related crashes in Connecticut and South Carolina, but the results were not statistically significant. It was determined that a sample size much larger than that available would be needed to detect a significant effect in these types of crashes. Given the very low cost of this strategy, even with conservative assumptions, only a very modest reduction in crashes is needed to justify its use. Therefore, this strategy has the potential to reduce crashes cost effectively, particularly at lower volume intersections.

INTRODUCTION

Background on Strategy

Intersections account for a small portion of the total highway system, yet in 2005, approximately 2.5 million intersection-related crashes occurred, representing 41 percent of all reported crashes. Intersection-related crashes account for more than 50 percent of total crashes in urban areas and over 30 percent of total crashes in rural areas. In addition, 8,655 fatal crashes (22 percent of the total 39,189 fatal crashes) occurred at or within an intersection environment in 2005.(1) The high frequency of crashes is not surprising, however, due to the fact that intersections present more points of conflict than non-intersections.

Unsignalized intersections often present potential hazards not associated with signalized intersections because of the priority of movement on the major roadway. This is often problematic on two-lane highways. Unsignalized intersections are usually found along low- to moderate-volume roads in rural and suburban areas that are generally associated with higher-speed travel than those in more developed suburban and urban areas.(2)

Driver compliance with intersection traffic control devices is vital to intersection safety. At stop-controlled intersections, drivers on the stop-controlled approach must identify and observe the STOP sign. Therefore, the STOP sign must be visible and conspicuous. This is particularly important during nighttime or other reduced visibility conditions such as rainy weather. One method to increase both the visibility and conspicuity of STOP signs is to use higher retroreflectivity sheeting.

Retroreflectivity is the property of a material that reflects a large portion of the light directly back to the source, through a wide range on angles of incidence of illumination. When applied to a sign, retroreflective sheeting will redirect light from the driver's headlights back to the driver's eyes. The amount of light from an object reaching the driver's eyes will have a great impact on the ability of a driver to see that object. Retroreflective materials use micro-sized glass beads, either enclosed or encapsulated, or microprisms (cube corner reflectors) in the sign sheeting material. Variations in the technology result in differing levels of retroreflectivity. A higher retroreflectivity measure will return a greater amount of light to the driver's eye at night, hence making the retroreflective object more visible.(3) While the difference in sign brightness (retroreflectivity) provided by different sheeting types cannot be illustrated adequately by photography, figure 1 does provide a relative visual comparison of STOP signs with six different grades of retroreflective sheeting. The American Society for Testing and Materials (ASTM) develops technical standards for industry worldwide. This includes retroreflective sheeting which is included in ASTM's *D495—Standard Specification for Retroreflective Sheeting and Traffic Control*.(4) ASTM Type I and II are commonly known as Engineering Grade and Super-Engineering Grade, respectively. Both are made with glass bead compositions. ASTM Type III, commonly known as High Intensity, is made with an encapsulated glass bead technology, while Types VII, VIII, and IX are manufactured with microprismatic technology.(4)

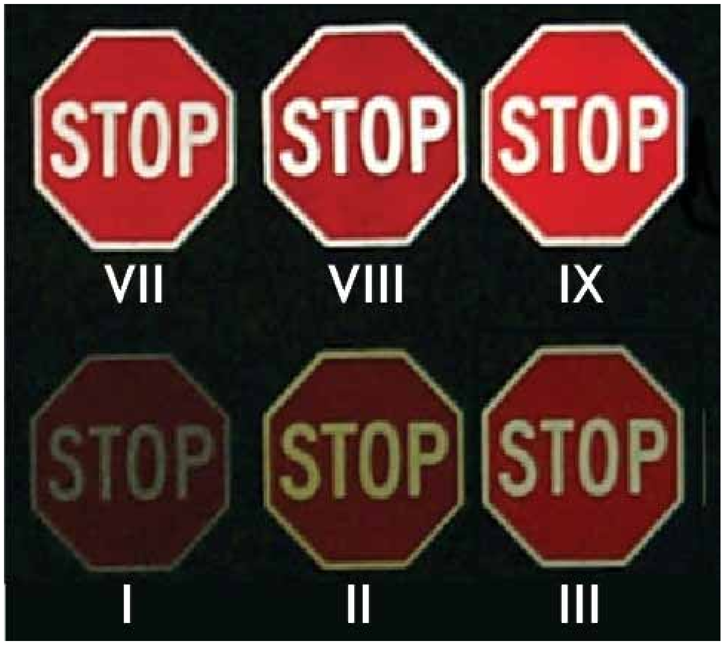

Figure 1. Image. Relative Visual Comparison of Sheeting Types.

The strategy to change to STOP signs with higher retroreflectivity was implemented in Connecticut from 1998 to 2001 and in South Carolina from 1997 to 2004 in an effort to reduce crashes at unsignalized intersections.

Background on Study

In 1997, the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee for Highway Traffic Safety, with the assistance of the FHWA, the National Highway Traffic Safety Administration (NHTSA), and the Transportation Research Board (TRB) Committee on Transportation Safety Management, met with safety experts in the field of driver, vehicle, and highway issues from various organizations to develop a strategic plan for highway safety. These participants developed 22 key areas that affect highway safety. One of these areas is unsignalized intersection crashes.

The National Cooperative Highway Research Program (NCHRP) published a series of implementation guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses one of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as proven, tried, or experimental. Many of the strategies discussed in these guides have not been rigorously evaluated; about 80 percent of the strategies are considered tried or experimental.

The FHWA organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of this strategic highway safety effort. The purpose of the Pooled Fund Study is to evaluate the safety effectiveness of several tried and experimental low-cost safety strategies through scientifically rigorous crash-based or simulation-based studies. Based on inputs from the Pooled Fund Study Technical Advisory Committee and the availability of data, installing higher retroreflective STOP signs was selected as a strategy that should be evaluated as part of this effort.

Literature Review

The literature review did not uncover any studies that specifically evaluated the safety effects, in terms of crash frequency and severity measures, of increasing retroreflectivity levels of STOP signs. There has been research, however, that shows increased driver visibility distance provided by increased retroreflectivity levels. This research includes a study by Carlson and Hawkins, which investigated the legibility effects of increasing the retroreflectivity of freeway guide signs.(5) In this study, ASTM Type III and Type IX retroreflective sheeting were analyzed. A total of 60 subjects, both young and old, participated in this nighttime study. The measure of effectiveness used in this study was legibility distance. The statistical test used was a mixed-factor repeated-measures analysis of variance (ANOVA). The ANOVA test indicated that sheeting type was statistically significant ($F_{1,116} = 34.69$, p-value < 0.0001). The improvement associated with increasing the retroreflectivity was nearly a 10-percent (16.2-m (53.0-ft)) increase in visibility distance. The link between visibility and crashes has not been established; therefore, no safety inference can be made from this finding.

OBJECTIVE

This research examined the change in crash frequency due to increasing the retroreflectivity of STOP signs at unsignalized intersections. The desired objective was to identify sites with crashes related to poor visibility due to the retroreflectivity of the STOP sign in the before period and estimate the expected change in crashes due to increasing the reflectivity using the EB method. While this is a worthy objective, it was not possible to determine those sites that had poor retroreflectivity in the before period because this was a blanket strategy. Although the type of sign (Type I, Engineer Grade) used in the before period was known, the exact condition including age of the signs or any degree of deterioration that occurred on each of the signs was not known. In addition, there were very few nighttime crashes, which made it difficult to identify a sufficient sample of sites that had crashes related to low retroreflectivity. Therefore, the objective was modified to estimate, in general, the safety effectiveness of this strategy as measured by crash frequency. Target crash types considered included the following:

- All intersection-related crash types.
- Injury crashes (includes K, A, and B on KABCO scale).
- Right-angle (side impact) crashes.
- Rear-end crashes.
- Daytime crashes.
- Nighttime crashes.

The range of safety effects was expected to vary by crash type; therefore, a second objective was to estimate, if necessary, the overall effect of the strategy by considering the economic costs by crash type and crash severity using crash costs recently developed for FHWA.[6]

A further objective was to address questions of interest such as:

- Do effects vary by traffic volumes?
- Do effects vary by approach speeds?
- Do effects vary by number of lanes?

Meeting these objectives placed some special requirements on the data collection and analysis tasks. These were:

- The need to select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.
- The need to properly account for traffic volumes changes.
- The need to pool data from more than one jurisdiction to improve reliability of the results and facilitate broader applicability of the products of the research.

STUDY DESIGN

The study design involved a sample size analysis and the prescription of needed data elements. The sample size analysis assessed the size of sample required to statistically detect an expected change in safety. Assumptions on the expected safety effects, on the average crash frequency at potential strategy sites in the before period, and on the average number of after period years of available data are basic to estimating sample sizes. Following a literature review and the application of methodology in Hauer, a minimum sample size was estimated.[7]

For this analysis, it was assumed at the time that the study was designed that a conventional before-after study with comparison group design would be used, since available sample size estimation methods are based on this assumption. To facilitate the analysis, it was also assumed that the number of comparison sites is equal to the number of strategy sites. The sample size estimates provided would be conservative in that state-of-the-art EB before-after methodology actually proposed for the evaluations would require fewer sites.

Sample sizes were estimated for various assumptions of likely safety effect and crash frequencies before the strategy was installed. Table 1 provides the crash frequency assumptions used. Rate A is based on a Minnesota study.[8] Rate B is based on an Ohio Study.[9] Rate C is based on Minnesota data from FHWA-RD-03-0037.[10] Right-angle and rear-end proportions were adopted from SafetyAnalyst development data.[11] The literature review provided no sound basis for an assumption on the expected safety effect. Thus, the analysis was based on logical values for this parameter.

Table 1. Before Period Crash Rate Assumptions.

Crash Type	Rate A (crashes/ intersection/year)	Rate B (crashes/ intersection/year)	Rate C (crashes/ intersection/year)
All	3.45	7.62	0.44
Right-Angle (39% of total assumed)	1.35	2.97	0.17
Rear-End (23% of total assumed)	0.79	1.75	0.10

Table 2 provides estimates of the required number of before period intersection-years in the sample for both the 90-percent and 95-percent confidence levels. The calculations assume equal number of intersection-years for strategy and comparison sites and equal length of before and after periods. Intersection-years are the number of intersections where the strategy was applied multiplied by the number of years the strategy was in place at each intersection. For example, if a strategy was applied at nine intersections and has been in place for three years at all 9 intersections, this is 27 intersection-years.

A minimum sample size of 1,076 intersection-years and a desirable sample size of 2,036 intersection-years per period were calculated as shown in bold in table 2. It was expected that these sample sizes could be reduced if the assumption for crashes per intersection-year before strategy implementation turns out to be conservatively low for strategy data, or if more after period years than assumed are available. The desirable sample assumes that the reduction in crashes could be as low as a 10-percent reduction in all crashes and that this is the smallest benefit that one would be interested in detecting with 90-percent confidence. The logic behind this approach is that safety managers may not wish to implement a measure that reduces crashes by less than 10 percent, and the required sample size to detect a reduction smaller than 10 percent would likely be prohibitively large. The minimum sample indicates the level for which a study seems worthwhile (i.e., it is feasible to detect with 90-percent confidence the largest effect that may reasonably be expected based on what is known currently about the strategy). In this case, a 20-percent reduction in right-angle crashes was assumed as this upper limit on safety effectiveness.

These sample sizes could be reduced if the assumption for crashes per intersection-year before strategy implementation turned out to be conservatively low for strategy data or if there are more after period years of data available than assumed.

Table 2. Minimum Required Before Period Intersection-Years for Treated Sites for Three Crash Rate Assumptions.

Expected Percent Reduction in Crashes		95% Confidence			90% Confidence		
		A	**B**	**C**	**A**	**B**	**C**
All	5	1,629	738	12,773	1,141	516	8,943
	10	371	168	2,907	260	118	**2,036**
	20	76	34	594	53	24	416
	30	27	12	211	19	9	147
	40	12	5	92	8	4	64
Right Angle	5	4,163	1,892	33,060	2,915	1,325	23,146
	10	948	431	7,525	663	302	5,268
	20	194	88	1,537	135	62	**1,076**
	30	69	31	545	48	22	381
	40	30	14	237	21	10	166
Rear End	5	7,114	3,212	56,203	4,981	2,249	39,349
	10	1,619	731	12,793	1,134	512	8,956
	20	331	149	2,612	232	105	1,829
	30	117	53	926	82	37	648
	40	51	23	403	36	16	282

Note: Bold denotes the calculated minimum and desirable sample size for intersection-years per period.

METHODOLOGY

The EB methodology for observational before-after studies was used for the evaluation.[7] This methodology is rigorous in that it accomplishes the following:

- It properly accounts for regression-to-the-mean.
- It overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- It reduces the level of uncertainty in the estimates of safety effect.
- It provides a foundation for developing guidelines for estimating the likely safety consequences of contemplated strategy.
- It properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

In the EB approach, the change in safety for a given crash type at a site is given by:

$$\Delta \text{ Safety} = \lambda - \pi , \tag{1}$$

Where:

λ	is the expected number of crashes that would have occurred in the after period without the strategy.
π	is the number of reported crashes in the after period.

In estimating λ, the effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types to traffic flow and other relevant factors for each jurisdiction *based on untreated sites*. Annual SPF multipliers were calibrated to account for the temporal effects on safety of variation in weather, demography, crash reporting, and so on.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (m) before strategy. This estimate of m is:

$$m = w_1(x) + w_2(P) \tag{2}$$

Where:

w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = \frac{P}{P + {}^{1}\!/_{k}} \tag{3}$$

$$w_2 = \frac{1}{k(P + {}^{1}\!/_{k})} \tag{4}$$

Where:

k	is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. (In that process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of this distribution.)

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = \frac{{}^{\pi_{sum}}\!/_{\lambda_{sum}}}{1 + \left({}^{Var(\lambda_{sum})}\!/_{\lambda_{sum}^2} \right)} . \tag{5}$$

The standard deviation of θ is given by:

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}} . \tag{6}$$

The percent change in crashes is calculated as $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

DATA COLLECTION

A survey was conducted to collect data for several low-cost strategies. Two States, Connecticut and South Carolina, responded that they had installed a large number of STOP signs with increased retroreflectivity as a blanketed effort across the State to improve safety. In addition to the locations and dates of the STOP signs, additional data including roadway geometry, traffic, and crash data were collected in order to conduct the evaluation. This section provides a summary of the data assembled for the analysis.

Connecticut Data Collection

Background

The Connecticut Department of Transportation (ConnDOT) replaced over 7,000 STOP signs (R1-1) on State highways and town roads approaching State highways from December 1998 to May 2001. The signs were replaced as part of a comprehensive replacement program. The overall motivation for the effort was traffic safety. However, individual locations were not selected based on crash experience. Instead, the replacement was a blanketed effort at all stop-controlled intersections.

The existing STOP signs were made up of Type I, Engineer Grade reflective sheeting. The exact condition before replacement of each of the signs, including the age of the signs and the degree of deterioration, was unknown. The sheeting was upgraded to a material that provides relatively high retroreflectivity at large observational angles, which was designated by the ASTM as Type IX sheeting. (At the time the signs were installed there was not a Type IX reflective sheeting ASTM designation.)

ConnDOT provided installation data, roadway, and traffic data for use in this study. The data collected were entered into a database, designed specifically for use in this evaluation, and matched to crash data supplied by the University of Connecticut (UCONN). Details on the data are provided in the following sections.

Installation Data

The installation data provided by ConnDOT contained the town name, route number, intersecting road name, size of the sign, and the date the sign was replaced. Of the 7,000 sign locations provided by ConnDOT, 231 intersections were included in the evaluation. The primary motivation for selecting these 231 intersections was the availability of traffic volume data. This is discussed in the section on traffic data.

Of the intersections used in the evaluations, 762-mm (30-inch) STOP signs were installed at 218 intersections, 1,219.2-mm (48-inch) STOP signs were installed at 11 intersections, and a combination of 762-mm (30-inch) and 1,219.2-mm (48-inch) STOP signs were installed at the remaining 2 intersections.

Roadway Data

ConnDOT provided access to a 2004 electronic photo log of the roadway system. Roadway data were collected for each intersection from the photo log. This included the intersection log mile, number of intersection approaches, number of roadway lanes per approach, presence of a shoulder on each approach, presence of a median on each approach, presence of other warning measures (e.g., STOP AHEAD warning signs), and intersection illumination.

There was a concern that some of the STOP signs used in the evaluation had received subsequent strategies such as a signal or a flashing beacon. Based on the photo logs, 18 intersections were identified that had been signalized or a flashing beacon had been installed since the STOP signs were replaced. A list of energized signals, provided by ConnDOT, helped to identify other intersections that had received a signal, and the signalization date. ConnDOT also provided the dates of the flashing beacons installations.

Traffic Data

The primary reason many intersections were excluded from the evaluation was the lack of traffic volume data. In order to be included in the evaluation, traffic volume on the major road was needed both before and after the sign was replaced. In addition, there had to be a traffic count on the minor roadway in at least the before or after period, although both were preferred.

Volume data are available from three sources in Connecticut: average daily traffic (ADT) maps, electronic count data in a spreadsheet format, and special counts. The ADT maps are available in both hard copy and electronic (.pdf) formats from 1999 to 2004. Traffic counts are conducted every three years to develop these maps. The count locations vary from year to year; not all locations were counted on each map. The electronic count data contained the same information as the ADT maps but for a longer period. Electronic count data are available from 1995 to 2006. For the purposes of extrapolating counts from nearby intersections, spatial count maps (i.e., the ADT maps) are preferable to tabular count data.

The third source of volume data are special counts. ConnDOT provided paper copies of special counts. These are volume counts that are requested for a variety of reasons including signalization studies, citizen complaints, and traffic operations analysis.

The stop-controlled roadway was considered the minor roadway for this study. In most cases, this was also the lower volume roadway. There were a few three-legged intersections where the stop-controlled approach had a higher ADT than the nonstop-controlled approach. Therefore, there were a few intersections in the database where the minor roadway had a higher ADT than the major roadway.

Crash Data

The Connecticut Transportation Institute at the UCONN provided crash data from 1995 to 2004 for this study. These data were originally provided to UCONN by the ConnDOT. UCONN formatted the raw data into a more user-friendly version. These data included all crashes on State-maintained roadways and crashes on non-State-maintained roadways that occurred within

0.02 km (0.01 mi) of an intersection with a State-maintained roadway. Therefore, all intersections in this study included at least one State-maintained roadway.

During the evaluation, it was discovered that there were log-mile changes throughout the study period. That is, the same intersection could have two different log miles in two different years. This was due to changes in the Connecticut roadway system. ConnDOT supplied a file of where log mile changes have occurred. These were used to resolve the log mile changes.

South Carolina Data Collection

Background

District 1 of the South Carolina Department of Transportation (SCDOT) conducted a comprehensive replacement of over 6,000 STOP signs from 1997 to 2005. District 1 is located in central South Carolina and is comprised of Aiken, Kershaw, Lee, Lexington, Richland, and Sumter Counties. Data from Kershaw and Lexington counties were used for this study.

The existing signs were made of Type I Engineer Grade reflective sheeting. The exact age and condition of the signs prior to replacement was unknown. They were replaced with signs that had Type III high-intensity reflective sheeting. The signs were replaced as part of a comprehensive replacement program.

SCDOT provided installation data, roadway, traffic, and crash data for use in this study. The data collected were entered into a database, designed specifically for use in this evaluation, and matched to crash data. Details on the data are provided in the following sections.

Installation Data

SCDOT provided a database of sign installations. For each sign, the database included the county, route, milepoint, direction, installation date, and sheeting type. Out of the more than 6,000 signs, 108 intersections were used in the evaluation. As with the Connecticut data, this was largely due to the availability of the traffic data. Of the 108 intersections, 93 had 762-mm (30-inch) STOP signs installed, and 15 had 1,219.2-mm (48-inch) STOP signs installed.

Roadway Data

SCDOT provided a copy of the roadway and traffic data that were collected for the Highway Performance Monitoring System (HPMS). The HPMS is a national highway information system that includes data on the extent, condition, performance, use, and operating characteristics of the Nation's highways. This database provided data on the land use (i.e., urban or rural), number of lanes, lane width, presence of a shoulder, shoulder width, presence of a median, and median type for each intersection approach. The speed limit was also available for 35 of the intersections.

Traffic Data

The majority of the traffic volumes used for this study were extracted from the HPMS files. These values came from a segment of roadway ranging from 0.16 to 8.05 km (0.1 to 5.0 mi) or more in length. The range was less in urban areas and greater in rural areas. Therefore, in rural areas, the volume count used to describe the volume entering the intersection may be collected from a point up to 8.05 km (5 mi) from the intersection. There were no records of where in the segment the count was actually collected.

For those locations where AADTs were not available through the HPMS, the AADT numbers were calculated from turning movement counts. Factors supplied by SCDOT were used to calculate the AADTs from the raw turning movement count data.

Crash Data

SCDOT supplied crash data in two databases. One database contained crashes occurring from 1994 to 2000. The second database contained crashes occurring from 2001 to 2005. The second database system was necessary because the crash data report and some associated variables were modified in 2001. In addition, prior to 1997, there was no threshold on reporting property damage only crashes. Starting in 1997, only crashes involving an injury or property damage greater than $1,000 were reported in the system.

Based on guidance from the SCDOT, the crash milepost was not used to locate crashes. Instead, the variable "base-offset distance" was used to identify crashes occurring at intersections.

Summary of Data

The analysis included a total of 3,323.8 intersection-years of data (2,038.6 intersection-years from CT and 1,285.2 intersection-years from SC). This sample was greater than the 1,076 intersection-years estimated in the study design required to detect a 20-percent reduction in right-angle crashes and the 2,036 intersection-years required to detect a 10-percent reduction in all crashes.

Table 3 provides crash definitions used in the two States. This information is crucial in applying the safety effect estimates in other jurisdictions.

Table 3. Definitions of Crash Types.

State	Intersection-Related	Injury	Right-Angle	Rear-End	Daytime	Nighttime
SC	Within 264 ft of intersection	K, A or B on KABCO scale	Defined as angle	Defined as rear-end	Daylight, dawn, dusk	Dark
CT	Within 264 ft of intersection, within 0.01 mi on minor	K, A or B on KABCO scale	Defined as angle or turning-intersecting paths	Defined as rear-end	Daylight, dawn, dusk	Dark

1 ft = 0.305 m
1 mi = 1.61 km

Table 4 and table 5 provide summary information for the data collected. This information should not be used to make simple before-after comparisons of crashes per site-year since such an analysis would not account for factors other than the strategy that may cause safety to change between the two periods. Such comparisons are properly done with the EB analysis as presented in subsequent sections.

Table 4. Data Summary for South Carolina Sites (n = 108).

Variable	Mean	Minimum	Maximum
Months before	100.7	45.0	144.0
Months after	42.1	2.0	99.0
Crashes/site-year before	2.1	0.0	16.1
Crashes/site-year after	2.0	0.0	18.9
Injury crashes/site-year before	0.7	0.0	3.8
Injury crashes/site-year after	0.6	0.0	6.0
Right-angle crashes/site-year before	0.8	0.0	7.1
Right-angle crashes/site-year after	0.7	0.0	6.4
Rear-end crashes/site-year before	0.7	0.0	7.1
Rear-end crashes/site-year after	0.7	0.0	12.9
Daytime crashes/site-year before	1.7	0.0	13.9
Daytime crashes/site-year after	1.6	0.0	15.4
Nighttime crashes/site-year before	0.4	0.0	2.5
Nighttime crashes/site-year after	0.4	0.0	3.7
Major road AADT before	9,847	413	53,587
Minor road AADT before	2,017	218	7,970
Major road AADT after	10,414	344	57,353
Minor road AADT after	2,139	206	9,178

Table 5. Data Summary for Connecticut Sites (n = 231).

Variable	Mean	Minimum	Maximum
Months before	59.7	48.0	84.0
Months after	46.2	3.0	60.0
Crashes/site-year before	1.9	0.0	18.9
Crashes/site-year after	2.4	0.0	32.0
Injury crashes/site-year before	0.7	0.0	5.9
Injury crashes/site-year after	0.8	0.0	6.7
Right-angle crashes/site-year before	0.5	0.0	3.6
Right-angle crashes/site-year after	0.6	0.0	4.0
Rear-end crashes/site-year before	0.6	0.0	10.6
Rear-end crashes/site-year after	0.9	0.0	11.8
Daytime crashes/site-year before	1.4	0.0	14.1
Daytime crashes/site-year after	1.8	0.0	22.0
Nighttime crashes/site-year before	0.5	0.0	5.1
Nighttime crashes/site-year after	0.6	0.0	10.0
Major road AADT before	7,690	929	29,816
Minor road AADT before	2,033	68	18,074
Major road AADT after	8,021	969	31,267
Minor road AADT after	2,122	71	18,879

DEVELOPMENT OF SPFS

This section presents the SPFs that were developed for use in the EB methodology. Generalized linear modeling was used to estimate model coefficients using the software package SAS® and assuming a negative binomial error distribution, which is consistent with the state of research in developing these models.

SPFs were calibrated separately for South Carolina and Connecticut. The reference groups used to develop SPFs were the same as the strategy groups since the installations were blanketed across the jurisdictions. The approach taken was as follows:

1. Combine the before and after period data to develop SPFs.

2. Recalibrate each SPF separately for the before and after periods to develop yearly multipliers.

Since the installations were over a multiyear period, it was possible to represent yearly trends in crash counts in an unbiased way that would not be possible if all installations occurred in the same year.

The primary form of the SPFs is:

$$\text{Crashes/year} = \alpha\,(\text{maj})^{\beta 1}\,(\text{maj})^{\beta 2} \tag{7}$$

Where:

maj	is major road entering AADT.
min	is minor road entering AADT.
α, $\beta 1$ and $\beta 2$	are parameters estimated from data in the SPF calibration process.

In some cases, the separate exponents could not be estimated with significance and the following Safety Function (SF) form was used:

$$\text{Crashes/year} = \alpha\,(\text{AADT})^{\beta 0} \tag{8}$$

Where:

AADT	is the total entering AADT.
$\beta 0$	is a parameter estimated from data in the SPF calibration process.

Using additional variables did not significantly improve the models. In specifying a negative binomial error structure, the "dispersion" parameter, *k*, which relates the mean and variance of the SPF estimate and is used in equations 3 and 4 of the EB procedure, is iteratively estimated from the model and the data. The value of *k* is such that the smaller its value, the better a model is for a given set of data.

The SPFs developed are presented in appendix A. Note the following in interpreting the output:

- The value of α is obtained as the $e^{\ln(\alpha)}$,where $\ln(\alpha)$ is the model output.
- The value of the parameter *k* is used in the EB approach.
- The value for Pr > ChiSq gives the level at which the estimate is significant. For example, Pr > ChiSq = 0.05 indicates that the parameter estimate is statistically significant at the 5-percent level (or, alternatively, that the 95-percent confidence interval does not include a value of 0).

SPFs were estimated for the following crash classifications:

- Total (all severities and types combined).
- Injury (all crash types combined).
- Right angle (all severities combined).
- Rear end (all severities combined).

- Day (all severities and types combined).
- Night (all severities and types combined).

RESULTS

Based on the data, two sets of results were calculated and are presented in the following sections. One set contains aggregate results for each jurisdiction and for the two combined; the other set is based on a disaggregate analysis that attempted to discern factors that may be most favorable to increasing STOP sign retroreflectivity.

Aggregate Analysis

The aggregate results are shown in tables 6 through 8. Results significant at the 95-percent confidence level are bolded. Note that a negative sign indicates an increase in crashes.

The results indicate that there may be a slight effect in South Carolina, but this effect is too small to detect with statistical significance, as evidenced by the relatively large standard errors (i.e., substantially greater than one-half of the estimated effect). The exception is for rear-end crashes, for which the reduction in crashes is significant at the 95-percent confidence level as shown in table 6.

The aggregate effects are negligible and statistically insignificant for Connecticut, and for the two jurisdictions combined. There are no detectable effects for nighttime crashes, the primary targets of this measure, which is likely a result of the reality that there are relatively few of these crashes at the strategy sites.

These inconclusive results and the fact that they are based on non-selective implementations emphasize the need for a disaggregate analysis to see if significant effects can be detected for specific conditions. This analysis is presented in the next section.

Table 6. Results for 108 South Carolina Strategy Sites.

	Right-Angle	Rear-End	Night	Day	Injury	Total
EB estimate of crashes expected in the after period without strategy	266.5	257.4	134.5	559.6	220.1	692.9
Count of crashes observed in the after period	247	213	141	515	200	656
Estimate of percent reduction	7.6%	**17.5%**	-4.4%	9.1%	9.4%	5.4%
Standard error	7.6	7.3	10.8	5.3	8.1	4.9

Notes: Bold denotes results significant at the 95% confidence level. The negative sign indicates an increase in crashes.

Table 7. Results for 231 Connecticut Strategy Sites.

	Right-Angle	Rear-End	Night	Day	Injury	Total
EB estimate of crashes expected in the after period without strategy	483.3	663.6	510.8	1494.8	700.1	2,019.2
Count of crashes observed in the after period	512	729	478	1543	659	2025
Estimate of percent reduction	-5.8%	-9.7%	6.6%	-3.2%	6.0%	-0.2%
Standard error	6.2	5.7	5.5	3.6	4.8	3.1

Note: The negative sign indicates an increase in crashes.

Table 8. Combined Results for 339 South Carolina and Connecticut Strategy Sites.

	Right-Angle	Rear-End	Night	Day	Injury	Total
EB estimate of crashes expected in the after period without strategy	749.8	921.0	645.3	2054.4	920.2	2712.1
Count of crashes observed in the after period	759	942	619	2058	859	2681
Estimate of percent reduction	-1.2%	-2.2%	4.4%	-0.1%	6.7%	1.2%
Standard error	5.3	4.8	6.0	2.7	4.5	2.7

Note: The negative sign indicates an increase in crashes.

Disaggregate Analysis

Table 9 presents the results of the disaggregate analysis. Nighttime crashes are the primary targets of this measure and should be the basis for this analysis; however, there are too few of these crashes to facilitate a disaggregate analysis. The results of the disaggregate analysis are based on all crashes combined. Significant results at the 95-percent confidence level are shown in bold.

The three factors that provided indications of an association with crash effects are environment (urban versus rural), number of approach legs, and minor road entering AADT.

Table 9. Results of the Disaggregate Analysis.

Intersection Type	Sites	EB estimate of crashes expected in the after period without strategy	Count of crashes observed in the after period	Estimate of percent reduction (standard error)
SC urban	47	333.9	288	**13.7% (6.7)**
SC rural	61	360.0	368	-2.0% (7.0)
SC three-legged	48	354.7	299	**15.9% (6.3)**
SC four-legged	60	338.2	357	-5.3% (7.4)
SC three-legged, urban	20	172.9	128	**26.3% (8.3)**
SC four-legged, urban	27	160.0	160	0.05% (10.6)
SC three-legged, rural	28	181.8	171	6.3% (9.4)
SC four-legged rural	33	178.2	197	10.2% (10.2)
CT urban	190	1,789.5	1,830	-2.2% (3.3)
CT rural	41	229.7	195	15.4% (8.1)
CT three-legged	172	1,458.0	1,399	4.1% (3.5)
CT four-legged	59	559.2	625	-11.6% (6.3)
CT three-legged, rural	29	152.6	118	**23.1% (9.2)**
CT four-legged, rural	12	75.2	76	-0.2% (15.8)
SC ≤ 1200 minor AADT	42	219.0	165	**24.9% (7.2)**
SC > 1200 minor AADT	66	473.9	491	-3.4% (6.3)
CT ≤ 1000 minor AADT	90	509.0	437	**14.3% (5.6)**
CT >1000 minor AADT	141	1,510.7	1,588	-5.1% (3.7)

Notes: Bold denotes results significant at the 95% confidence level. The negative sign indicates an increase in crashes.

For the urban versus rural factor, there are opposing indications from the two States, with the more favorable effects for rural installations in Connecticut and urban installations in South Carolina.

For number of approaches (i.e., legs), a more consistent pattern emerges. For both States, in particular for the favored environment, installations at three-legged intersections appear to be more effective than at four-legged intersections.

For minor entering AADT, there is a consistent pattern that this strategy is more effective at lower volumes. The boundaries of 1,200 AADT in South Carolina and 1,000 in Connecticut were chosen to provide the most discrimination between upper and lower AADT levels in order to indicate the effect of this factor. Therefore, these numbers should not be used in decisions on whether or not to install a sign. The analysis does suggest, however, that lower minor road locations should be given higher priority if there is a need to prioritize locations (as should three-legged intersections).

Speculation on reasons for the differential effects found is undertaken in a discussion section later in the report. However, it should be pointed out that further investigation was undertaken to ensure that the effects found were not due to biases in the analysis. This further investigation involved an examination of the results of a naïve before-after study that simply compared crash frequencies pre- and post-strategy and did not use safety performance functions. The naïve before-after study yielded similar conclusions to the EB study regarding the influence of the three factors, but different magnitudes for the crash effects for the various groupings in table 9. The project team also investigated whether the findings regarding the differential effects for one factor may have been confounded by co-linearity of this factor with another for which similar effects were found. For example, this investigation revealed that the conclusion regarding minor road AADT was equally relevant for three-legged and four-legged intersections and for urban and rural intersections. As shown in table 9, the finding regarding three-legged versus four-legged intersections is equally valid for urban and rural environments.

Data were available for an analysis of other possible factors that might influence crash effects. However, no such effects could be ascertained. The other factors examined were sign size (762 mm (30 inches) versus 1,219.2 mm (48 inches)), the presence of lighting (for Connecticut), the presence of other measures such as STOP AHEAD signs, the major road entering volume, and the expected crash frequency prior to strategy. For sign size, there were very few that were of the 1,219.2-mm (48-inch) variety and so, statistically, it was difficult to detect different crash effects for the two sign sizes, even if such differences exist.

ECONOMIC ANALYSIS

The purpose of this analysis was to determine the economic feasibility of applying this strategy. The life-cycle costs of the strategy were estimated and expressed as an annual cost. The crash benefits required to offset these costs were estimated using the most recent FHWA unit crash cost data for unsignalized intersections. The results of the aggregate and disaggregate analysis of crash effects were used to make a judgment on the circumstances that would be favorable to ensuring economic feasibility (i.e., circumstances that may yield a benefit cost ratio of at least 2:1).

Cost data provided by the two States suggest a conservatively high initial cost of about $200 per intersection, considering the mix of three-legged and four-legged intersections and sign sizes. State sources also suggest an expected sign life of 8 years, again conservatively estimated. Costs would be even lower if the marginal costs of replacing the signs were used. As of 2007, the approximate costs of sheeting are as follows:

- Type I sheeting is $0.75 per square foot.
- Type II sheeting is $1.25 per square foot.

- Types VII, VIII, and IX are $3.50 per square foot.

These would reflect the costs if a jurisdiction used higher retroreflective materials as part of its routine maintenance program, as opposed to replacing all of the existing signs across a jurisdiction at one time regardless of the condition of the existing signs, as was done in Connecticut and South Carolina.

Based on the Office of Management and Budget suggested discount rate of 7 percent, and on the expected service life (8 years), the initial costs per intersection were converted to annual costs using the standard economics formula for a capital recovery factor. The more conservative $200 initial cost translates into an annual cost of around $33 over the 8-year cycle, requiring an annual crash saving of more than $66 per intersection for a benefit cost ratio of at least 2:1.

The most recent FHWA mean comprehensive costs per crash for unsignalized intersections are $13,238 for rear-end and $61,114 for right-angle crashes.(6) Comprehensive crash costs represent the present value, computed at a discount rate, of all costs over the victim's expected life span that result from a crash. The major categories of costs used in the calculation of comprehensive crash costs include medical-related costs, emergency services, property damage, lost productivity, and monetized quality-adjusted life years.(6) By applying the more conservative figure, $13,238, a $66 saving would require a reduction of approximately 0.005 crashes per intersection per year. This is a reduction of approximately 0.5 percent for rural Connecticut intersections, which have an annual crash frequency of 1.11, the lowest of the four State/environment groups. This reflects the more conservative costs of replacing all existing signs across a jurisdiction at one time with signs with retroreflective material regardless of condition of the existing signs.

Even with the conservative assumptions made, just a very modest reduction in crashes is required to justify this strategy economically. The evidence suggests that this reduction is easily achievable, in particular, under the circumstances identified from the disaggregate analysis.

SUMMARY

The objective of this study was to evaluate the safety effectiveness as measured by crash frequency of higher retroreflective sheeting on STOP signs at unsignalized intersections. The study was designed to detect a 10-percent reduction in all crashes with 90-percent confidence. The study also examined the effects of higher retroreflectivity on specific crash types. While it is desirable to evaluate the effectiveness of this strategy on related crashes (i.e., nighttime, low-visibility), there was not a sufficient number of related crashes to determine an effect with confidence.

The aggregate analysis indicates that higher retroreflective STOP signs may affect the likelihood of crashes at unsignalized intersections, but the effect is not detectable with the study design and available sample size. The exception is for rear-end crashes in South Carolina, where there was a significant reduction.

The disaggregate analysis provided further insight into the circumstances where crash reductions were identified. Installations at three-legged intersections (indiscriminate or urban/rural factor) and three-legged urban intersections in South Carolina were found to have a statistically significant reduction in crashes. In Connecticut, a statistically significant reduction in crashes was found for three-legged rural intersections. The disaggregate analysis also showed that the strategy is more effective at lower volumes for motorists approaching the intersection along the minor road. Statistically significant reduction in crashes were found at intersections with approaching volumes of less than 1,200 in South Carolina and less than 1,000 in Connecticut. This volume related finding is expected. At higher volume intersections, there are more visual cues for the approaching minor road motorist that the intersection is stop-controlled. Most notably, other traffic stopped in front of the driver on the approach is a visual cue.

For the urban versus rural factor, there are opposing indications from the two States, with the more favorable effects for rural installations in Connecticut and urban installations in South Carolina. There was no explanation available for these inconsistent results between the two States.

There are no detectable effects for nighttime crashes. As discussed previously, this might be because there are relatively few of these crashes at the strategy sites. It is also likely that this is because these are blanket installations and the significant benefits at relatively few nighttime crash problem locations become diluted by the negligible effects at other locations. To establish the benefits for nighttime crashes with statistical significance would require a database with a substantial number of sites at which this strategy was implemented because of a high frequency of nighttime crashes perceived to be "correctable" by this strategy. The sample size required for such a special database would be of a similar order of magnitude to that required for the database for the blanketed installations.

It should be noted, however, that the study results do not support the degradation of signs below any desired retroreflectivity requirements. The results are based on a blanket improvement with no knowledge of the previous sign conditions. This being the case, it is difficult to determine the safety effectiveness of more highly retroreflective sheeting on STOP signs for specific conditions. There was not a large enough sample size to detect any significant effects. The sample size required to detect a significant effect would be outside the scope of this project. As indicated in the FHWA Supplemental Notice of Proposed Amendments, improving sign retroreflectivity will be a benefit to all drivers, including older drivers.(12) All drivers need legible signs in order to make important decisions at key locations, such as intersections and exit ramps on high speed facilities. This is particularly true for regulatory and warning signs.

CONCLUSION

A minimal reduction in crashes can be expected with the installation of higher retroreflective STOP signs. However, given the very low cost of this strategy, even with conservative assumptions, only a very modest reduction in crashes is needed to justify their use. Therefore, this strategy has the potential to reduce crashes cost effectively, particularly at lower volume intersections.

APPENDIX A: SOUTH CAROLINA SAFETY PERFORMANCE FUNCTIONS (SPFS)

Table 10. Total—All Severities.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
$\ln(\alpha)$	-7.9320	1.7537	<.0001	-10.5902	2.6984	<.0001
$\beta 0$						
$\beta 1$	0.5990	0.1309	<.0001	0.6639	0.2299	0.0039
$\beta 2$	0.4331	0.1652	0.0087	0.6460	0.2170	0.0029
k	0.6494	0.1253		1.1429	0.2385	

Note: The negative sign indicates an increase in crashes.

Table 11. Injury—All Types.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
$\ln(\alpha)$	-7.2994	2.0709	0.0004	-11.5587	2.7736	<.0001
$\beta 0$						
$\beta 1$	0.4866	0.1491	0.0011	0.6890	0.2386	0.0039
$\beta 2$	0.3401	0.1912	0.0753	0.5893	0.2091	0.0048
k	0.7322	0.1652		0.8016	0.2096	

Note: The negative sign indicates an increase in crashes.

Table 12. Right-Angle—All Severities.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-8.9674	2.1553	<.0001	-10.0403	3.0644	0.0011
β0						
β1	0.6588	0.1516	<.0001	0.5194	0.2731	0.0572
β2	0.3689	0.2044	0.0711	0.6448	0.2642	0.0147
k	0.8566	0.1899		1.5344	0.3539	

Note: The negative sign indicates an increase in crashes.

Table 13. Rear-End—All Severities.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-15.3916	3.1187	<.0001	-16.4839	4.3121	0.0001
β0						
β1	1.0693	0.2289	<.0001	1.0228	0.3342	0.0022
β2	0.6968	0.2495	0.0052	0.8386	0.2947	0.0044
k	1.2372	0.2744		1.7207	0.4234	

Note: The negative sign indicates an increase in crashes.

Table 14. Day—All Severities and Types.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-9.6967	1.9103	<.0001	-9.0236	2.9690	0.0024
β0						
β1	0.7080	0.1413	<.0001	0.5947	0.2581	0.0212
β2	0.5015	0.1761	0.0044	0.5143	0.2401	0.0322
k	0.7423	0.1498		1.4078	0.2902	

Note: The negative sign indicates an increase in crashes.

Table 15. Night—All Severities and Types.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-3.8185	1.6073	0.0175	-7.2487	3.1635	0.0219
β0	0.3381	0.1728	0.0504	0.6526	0.3382	0.0536
β1						
β2						
k	0.6292	0.1496		1.0298	0.2840	

Note: The negative sign indicates an increase in crashes.

APPENDIX B: CONNECTICUT SPFS

Table 16. Total—All Severities.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-8.9117	2.7596	0.0012	-7.2564	1.1264	<.0001
β0	1.0156	0.3127	0.0012			
β1				0.6607	0.1069	<.0001
β2				0.2883	0.0649	<.0001
k	1.1312	0.2959		1.1736	0.1312	

Note: The negative sign indicates an increase in crashes.

Table 17. Injury—All Types.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-7.8518	3.1177	0.0118	-8.6687	1.1143	<.0001
β0	0.7967	0.3529	0.0240			
β1				0.6715	0.1096	<.0001
β2				0.3149	0.0628	<.0001
k	1.2010	0.3581		0.9519	0.1266	

Note: The negative sign indicates an increase in crashes.

Table 18. Right-Angle—All Severities.

Parameter	Urban		
	Estimate	Standard Error	Pr > ChiSq
ln(α)	-7.1373	1.3875	<.0001
β0			
β1	0.4303	0.1297	0.0009
β2	0.3670	0.0817	<.0001
k	1.2848	0.1734	

Note: The negative sign indicates an increase in crashes.

A model for rural night, all severities and types, crashes could not be estimated. A proportion of 26.7 percent of total crashes was used; that is, a factor of 0.267 to the rural total crash SPF was applied.

Table 19. Rear-End—All Severities.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-18.4262	3.7098	<.0001	-12.4637	1.3882	<.0001
β0						
β1	1.1696	0.3556	0.0010	1.0315	0.1300	<.0001
β2	0.9914	0.2073	<.0001	0.3829	0.0746	<.0001
k	0.9103	0.3719		1.4777	0.1906	

Note: The negative sign indicates an increase in crashes.

Table 20. Day—All Severities and Types.

Parameter	Rural			Urban		
	Estimate	Standard Error	Pr > ChiSq	Estimate	Standard Error	Pr > ChiSq
ln(α)	-10.0048	2.3582	<.0001	-7.8070	1.1413	<.0001
β0						
β1	0.3965	0.2239	0.0766	0.6752	0.1085	<.0001
β2	0.8869	0.1495	<.0001	0.3056	0.0653	<.0001
k	0.6789	0.2349		1.1850	0.1359	

Note: The negative sign indicates an increase in crashes.

Table 21. Night—All Severities and Types.

Parameter	Urban		
	Estimate	Standard Error	Pr > ChiSq
ln(α)	-7.9631	1.1996	<.0001
β0			
β1	0.6405	0.1155	<.0001
β2	0.2202	0.0671	0.0010
k	1.0040	0.1377	

Note: The negative sign indicates an increase in crashes.

A model for rural night, all severities and types, crashes could not be estimated. A proportion of 24.0 percent of total crashes was used; that is, a factor of 0.267 to the rural total crash SPF was applied.

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