Final Technical Content

Investigation of Existing and Alternative Methods for Combining Multiple CMFs

Task A.9

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Introduction

There is a need to investigate current practices for applying multiple crash modification factors (CMFs). Transportation agencies frequently implement multiple treatments at a given location, either sequentially or simultaneously, to address specific safety concerns. These agencies need to estimate the expected safety impact of the combined treatments and CMFs are one tool to support this effort. The issue is that relatively few CMFs have been developed for specific combinations of treatments and it would take a tremendous effort to develop CMFs for all likely combinations of treatments. There are numerous CMFs available for individual treatments and somehow combining individual CMFs to estimate the combined treatment effect is one alternative to developing CMFs for each possible combination of treatments. Currently, there is limited guidance on the application of multiple CMFs, and the guidance that does exist has not been rigorously tested.

A CMF is a multiplicative factor used to estimate the expected number of crashes after implementing a given countermeasure at a specific site. CMFs may be related to total crashes or specific crash types and/or severities. It is not appropriate to apply a CMF for a specific crash type or severity to other crash types and severities because a countermeasure may reduce certain crashes while increasing others. A CMFunction is an equation used to compute a CMF based on other factors (e.g., traffic volume) when the CMF cannot be represented as a single value. The Highway Safety Manual, CMF Clearinghouse, and other related resources provide more than 3,000 CMFs for various safety strategies.

The Highway Safety Manual and other related resources provide basic guidance on the application of CMFs and limited guidance on the application of multiple CMFs. Specifically, the Highway Safety Manual indicates that CMFs are multiplicative where treatments are installed concurrently and are presumed to have independent effects (i.e., CMFs may be multiplied to estimate a combined effect when there are multiple treatments that address different crash types). As a note of caution, it is not appropriate to simply multiply the CMFs if the respective CMFs are related to different crash types and/or severities, even if multiple treatments are independent. In this case, the combined effect can still be estimated, but the CMFs would be applied individually to the specific crashes expected for that crash type and/or severity. The Highway Safety Manual also cautions the user that the combined effect of multiple treatments may be over-estimated if the CMFs are multiplied and engineering judgment is necessary to assess the interrelationships and independence of multiple treatments.

The intended audience for this document is state and local transportation agencies and the consultants supporting them in their safety management efforts. Specifically, this document is intended to bring to light several issues associated with the application of multiple CMFs and provide guidance on how to estimate the combined treatment effect when multiple treatments are installed at a given location. This paper presents several existing methods for combining multiple CMFs and discusses the associated issues. Next, several ideas are explored for overcoming the identified issues. Finally, the methods are applied and compared to existing CMFs for multiple treatments in an attempt to validate the new procedures.

Definitions

This section provides several basic definitions and conversions that will be referred to throughout the document.

Crash modification factor (CMF): A CMF is a multiplicative factor used to estimate the expected number of crashes after implementing a given countermeasure at a specific site.

Crash modification function (CMFunction): A CMFunction is an equation used to compute a CMF based on other factors (e.g., traffic volume) when the CMF cannot be represented as a single value.

Crash reduction factor (CRF): A CRF is similar to a CMF and represents the expected percent reduction in crashes after implementing a given countermeasure at a specific site. The CRF is generally given in percent form (e.g., CRF = 25 represents a 25 percent reduction in crashes). However, the CRF could also be given in decimal form (e.g., CRF = 0.25 represents a 25 percent reduction in crashes).

Relationship between CMF and CRF: There is a direct relationship between a CMF and CRF. Assuming the CRF is in decimal form, the CMF can be calculated as one minus the CRF [CMF = 1 – CRF]. The opposite also holds where the CRF can be calculated as one minus the CMF.

Existing Methods for Combining Multiple CMFs

Review of Survey Information from NCHRP Project 17-25

As part of NCHRP Project 17-25, a survey was conducted to determine current agency practices for the application of CMFs. The survey results identified several different methods for applying multiple CMFs. The results of the survey are summarized in this section to provide a starting point for further exploration of the strengths and weaknesses of methods to combine multiple CMFs.

Table 1 presents 11 different methods related to the application of CMFs. Each method is presented along with the state(s) in which the method is/was applied. Note that these results are based on a survey conducted in 2003. As such, agency practices may have changed since that time. The specific state in which each method is applied is not relevant to this exercise. Rather, it is sufficient to identify specific methods that are or have been applied to estimate the effects of multiple treatments.

TABLE 1. Methods for Combining Multiple CMFs (from NCHRP Project 17-25)

Number	Method	State(s)
1	$CMF_t = CMF_1 - \frac{1 - CMF_2}{2} - \cdots - \frac{1 - CMF_n}{n}$ CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment CMF_n = CMF for the n^{th} treatment	Alabama
2	$CMF_t = CMF_1 * CMF_2$ CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment Note: Approach 2 and Approach 3 are equivalent when there are only 2 countermeasures.	Maine, Minnesota, Utah
3	$CMF_t = CMF_1 * CMF_2 * \ldots * CMF_n$ CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment CMF_n = CMF for the n^{th} treatment	Florida, Maryland, Ohio, Oregon, Pennsylvania, Vermont, Washington
4	CMFs are organized into six groups based on their application. Group I factors are applied to all crashes. Group II factors are applied according to severity. Group III factors are applied by crash type. Group IV factors apply to wet pavement crashes. Group V factors applied to night crashes. Group VI factors apply to train-related crashes. If multiple treatments are applied to the same type of crash, then Approach 3 is used.	Missouri
5	CMFs are developed using a weighted average of types of improvements based on the collision pattern at the location.	California

Number	Method	State(s)
6	A CMF is determined based on existing CMFs, previous experience, and engineering judgment.	Colorado
7	The CMF for each type of crash is applied separately to the target crashes. The resulting crash reductions are summed to develop a project CMF. The CMFs used for this method were obtained from a 1996 study conducted by the University of Kentucky (*1*).	Delaware
8	Only one treatment can be applied in the analysis to any one crash.	Michigan
9	Only the lowest CMF is applied (i.e., treatment with the greatest expected crash reduction).	South Carolina
10	The crash patterns at the location are considered and then judgment is applied.	West Virginia

Highway Safety Manual

The recently published Highway Safety Manual (HSM) presents a method for combining multiple CMFs. Equation 1 summarizes this relationship (*2*):

$$N = N_{base}(CMF_1 * CMF_2 * CMF_n) \quad (1)$$

Where:

N = predicted crash frequency for a given roadway segment or intersection.

N_{base} = predicted crash frequency under base conditions (i.e., no countermeasures in place).

CMF_n = crash modification factor associated with countermeasure n.

The HSM method is equivalent to Approach 3 described earlier. The method adopted by the HSM assumes that the safety effect of each countermeasure is independent when multiple countermeasures are implemented. The assumption of independence produces a simple computational approach but lacks solid theoretical justification. For example, improving delineation along a curve and increasing the radius of the horizontal curve are countermeasures which both address run-off-road crashes; it is likely that the implementation of one of these two countermeasures would have an effect on the safety effectiveness of the other.

CMF Clearinghouse

The CMF Clearinghouse also provides limited guidance on how to combine multiple CMFs. It cautions users against always assuming that CMFs are independent. Specifically, the CMF Clearinghouse states that users should apply engineering judgment to determine if the assumption of independence among CMFs holds for a given set of countermeasures. Further, it suggests that the target crash types for a given set of countermeasures be considered prior to making such a judgment. If there is no overlap in the target crash type for a given set of countermeasures, then it may be safe to assume independence. In such a case, the method shown by Equation 1 from the HSM may be applicable. However, if there is some overlap in the target crash types for a given set of countermeasures, then the assumption of independence may not be valid. In that case, the CMF Clearinghouse states the method shown by Equation 1 would likely overestimate the crash reductions associated with the implementation of the combination of countermeasures. The CMF Clearinghouse does not currently propose a means of addressing this potential problem.

Meta-Analysis

Other methods for combining multiple CMFs have been proposed. One of these approaches is based on meta-analysis in which the results from various studies are combined. More specifically, in these meta-analyses the CMF estimates for the same countermeasure from numerous studies are combined. For example, meta-analyses have been conducted for the conversion of intersections to roundabouts, the construction of bypass roads, the installation of guardrails and crash cushions, and the installation of red light cameras (*3, 4, 5, 6*). Equation 2 has been suggested for combining CMFs for the same countermeasure (*7*).

$$\mathrm{CMF} = \frac{\sum_{i=1}^{n} \mathrm{CMF}_{\mathrm{unbiased},i}/S_i^2}{\sum_{i=1}^{n} 1/S_i^2} \qquad (2)$$

Where:

CMF = combined unbiased CMF value.

$\mathrm{CMF}_{\mathrm{unbiased},i}$ = unbiased CMF value from study i.

s_i = adjusted standard error of the unbiased CMF from study i.

n = number of CMFs to be combined.

The estimation of a confidence interval for the combined effect is also of interest. This is of particular interest when combining CMFs for multiple treatments, but there is currently no information available to estimate the confidence interval for this situation. The methods applied in meta-analysis may provide some direction on potential approaches to estimate a confidence interval for combined CMFs. Specifically, Equation 3 has been suggested to estimate the standard error when multiple CMFs for the same treatment are combined in a meta-analysis (*7*).

$$S = \sqrt{\frac{1}{\sum_{i=1}^{n} 1/S_i^2}} \qquad (3)$$

Where:

S = standard error of the combined unbiased CMF value.

S_i = adjusted standard error of the unbiased CMF form study i.

n = number of CMFs to be combined.

Though they provide important information, meta-analysis research studies that examine a single countermeasure fail to deliver what many practitioners are seeking: an estimate of the combined safety effect of applying different countermeasures. Nonetheless, meta-analysis methods like the one above may help to generate ideas on how to calculate a CMF estimate and standard error for the application of multiple countermeasures. There is scant literature to date on this topic. A method for separating the effects of multiple countermeasures has been proposed (*8)*; however, that objective is the exact opposite of what is sought here.

Crash Modification Functions

There is a possibility that an answer to addressing the challenge of applying multiple CMFs may be to utilize CMFunctions, complex safety performance functions, or crash prediction models. A CMFunction is similar to a CMF in that it produces a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure, but differs in that it uses a continuous function of one or more independent variables (e.g., traffic volume or speed) (*9*).

Elvik (*9*) outlines a methodology for developing CMFunctions in the context of meta-analysis research; however, CMFunctions may be formulated through other methods as well. In short, Elvik's method uses regression analysis and previous CMF research studies to produce a continuous function in which the dependent variable is an estimated CMF value and the independent variables are characteristics which affect safety performance. For example, when examining bypass roads in Norway, Elvik produced a CMFunction in which the independent variable was the population of the city where the roads were located. When examining the conversion of intersections to roundabouts, the independent variable was selected to be the diameter of the central island. The application of CMFunctions to address the issue of multiple CMFs may become clearer in the latter example. Since changing the diameter of the roundabout can be considered one countermeasure, the CMFunction is essentially estimating the safety effect of two countermeasures (i.e., conversion of intersection to roundabout and changing the roundabout diameter). The example of bypass roads in Norway reflects the original intent of CMFunctions, namely to account for systematic changes in safety due to some variable (e.g., city population) apart from the countermeasure itself (e.g., construction of bypass roads) (*9*). The independent variable(s) may or may not be directly associated with another countermeasure. The example of bypass roads in Norway illustrates a case in which the independent variable is not associated with a countermeasure whereas the latter example of conversion of intersections to roundabouts illustrates a case in which the independent variable is another countermeasure. Therefore, CMFunctions derived from meta-analysis research may not have been designed to address the issue of applying multiple CMFs, but they may offer a way of doing so under specific conditions.

CMFunctions have also been developed outside the context of meta-analysis research. In these cases, regression analysis is used but not with CMF estimates from prior studies as outlined by Elvik. Instead, regression analysis is employed such that the countermeasure is modeled as an independent variable within the model form of the CMFunction. If the model form contains one or more additional independent variables that can be associated with other countermeasures, then the CMFunction may be able to address the challenge of applying multiple CMFs. Dell'Acqua and Russo developed an elaborate CMFunction for roadways in Italy which may demonstrate how a CMFunction may be used in this context (*10*). The CMFunction they constructed for injury crashes on Italian roadways is shown by Equation 4. In this example, multiple roadway characteristics are linked and modeled, including roadway width, slope (i.e., flat, rolling, or mountainous terrain), and tortuosity (i.e., general curvature). CMFunctions attempt to address the issue of applying multiple CMFs in a way that is distinct from the other approaches described above. Unlike other approaches that select a way to combine point estimates, a CMFunction bypasses this need by explicitly modeling the countermeasures within a single model form.

$$y_1 = \left(\frac{ADT}{1000}\right)^{0.6444} * L_u * e^{(-11.7399+0.1739V+3.5583CP-3.7087CT-0.2514La)} \quad (4)$$

Where:

y_1 = the number of fatal crashes per year observed on roadway segment length $L_{u.}$
ADT = average daily traffic in vehicles/day observed in three years.
L_u = length of the analyzed roadway segment (km).
V= mean value for speed in free flow conditions on a selected roadway segment (km/h).
CP = slope coefficient equal to 0.8 for low slopes, 0.9 for high slopes and 1 for very high slopes.
CT = tortuosity coefficient of 0.8 for low tortuosity, 0.9 for high tortuosity and 1 for very high tortuosity.
L_a = roadway width in meters.

Issues Related to the Application of Multiple CMFs

There are several issues to consider on the matter of applying multiple CMFs. Six primary issues were identified from existing methods, including:

1. Assumption of Independence.
2. Logic of Added Benefit versus Fallacy of Additive Effects.
3. Lack of Consistency (Judgment).

4. Applicability of CMFs.
5. Lack of Detailed CMF Information.
6. Computing a Confidence Interval.

Each of these issues is discussed in detail.

Assumption of Independence

The overarching issue is the possibility that the safety effects of the countermeasures may not be independent of one another. In other words, the effect of the simultaneous or sequential application of countermeasures may not simply be the product of the CMFs for the individual countermeasures. Due to correlations among the CMFs, the true combined effect of multiple countermeasures may be greater than, less than, or equal to the simple product. Consider a basic situation in which there are two countermeasures represented by CMF1 and CMF2. The parameter of interest is the true safety effect of the combination of these two individual countermeasures ($\overline{CMF_{12}}$). As described in the HSM, the current practice is to simply multiply the two CMFs as was shown in Equation 1, if they are assumed to be independent. This assumption may lead to three different scenarios as characterized by Equations 5 – 7. The true safety effect of the combination of countermeasures may be overestimated (i.e., Equation 5), underestimated (i.e., Equation 6), or accurately estimated (i.e., Equation 7):

$$\overline{CMF_{12}} > CMF1 * CMF2 \quad (5)$$

$$\overline{CMF_{12}} < CMF1 * CMF2 \quad (6)$$

$$\overline{CMF_{12}} = CMF1 * CMF2 \quad (7)$$

Where:

$\overline{CMF_{12}}$= true safety effect of applying countermeasures 1 and 2 (i.e., parameter).

$CMF1 * CMF2$ = simple product of two crash modification factors (i.e., parameter estimate).

Examples of the first and third scenarios may be more familiar than examples of the second scenario (Equation 6). An example of the first scenario would be the implementation of two or more countermeasures that redundantly address the same crash type. For instance, installing roadway lighting and enhancing pavement marking retroreflectivity both address nighttime crashes. Since both countermeasures address nighttime crashes, it is possible that the crash reduction associated with the two countermeasures would be less than the value suggested by the product of the two CMFs. Examples of the second scenario would be the implementation of two or more countermeasures that significantly complement each other such that the combined crash reduction is greater than the sum of the parts. For instance, the cumulative effect of installing raised pavement markers, chevrons, and post-mounted delineators on run-off-road crashes may be greater than the value suggested by the product of the three CMFs. Examples of the third scenario may be the implementation of countermeasures that target different crash types. For instance, installing right- and left-turn lanes on the major approaches of an intersection will target specific, separate crash types. Since the target crash types are mutually exclusive, the combined effect may be computed accurately as the product of the individual CMFs.

In the case of three or more countermeasures, one may encounter another scenario in which the net combined effect of the countermeasures approximately equals the product of the individual countermeasures, but only because of offsetting correlations among pairs of countermeasures. For example, suppose there are three countermeasures being considered for implementation: CMF1, CMF2, and CMF3. The following scenario is possible:

$$\overline{\text{CMF}}_{12} \gg \text{CMF1} * \text{CMF2} \tag{8}$$

$$\overline{\text{CMF}}_{23} \ll \text{CMF2} * \text{CMF3} \tag{9}$$

$$\overline{\text{CMF}}_{13} = \text{CMF1} * \text{CMF3} \tag{10}$$

$$\text{Such that } \overline{\text{CMF}}_{123} = \text{CMF1} * \text{CMF2} * \text{CMF3} \tag{11}$$

Where:

$\overline{\text{CMF}}_{12}$= true safety effect of applying countermeasures 1 and 2 (i.e., parameter).

$\overline{\text{CMF}}_{23}$= true safety effect of applying countermeasures 2 and 3 (i.e., parameter).

$\overline{\text{CMF}}_{13}$= true safety effect of applying countermeasures 1 and 3 (i.e., parameter).

$\overline{\text{CMF}}_{123}$ = true safety effect of applying countermeasures 1, 2, and 3 (i.e., parameter).

$\text{CMF1} * \text{CMF2}$ = simple product of crash modification factor 1 and 2 (i.e., parameter estimate).

$\text{CMF2} * \text{CMF3}$ = simple product of crash modification factor 2 and 3 (i.e., parameter estimate).

$\text{CMF1} * \text{CMF3}$ = simple product of crash modification factor 1 and 3 (i.e., parameter estimate).

$\text{CMF1} * \text{CMF2} * \text{CMF3}$ = simple product of crash modification factor 1, 2, and 3 (parameter estimate).

This scenario and its various permutations are also noteworthy because decision-makers in the industry may be given the false impression that the contributions made by each pair of countermeasures can be estimated accurately as the product of the individual CMFs. As the above scenario demonstrates, it is possible that two of the three countermeasures account for the vast majority of the reduction in crashes (i.e., one of the countermeasures was relatively ineffective and therefore not cost-effective). As such, the remainder of this document focuses on the comparison and combination of CMFs from two countermeasures, and it is suggested that other CMF users only compare two countermeasures at a time to avoid the abovementioned complications.

These potentially troubling scenarios raise the question of how to determine when countermeasures are independent. One suggested approach is by examining the target crash types for each of the countermeasures *(11)*. If countermeasures target different crash types, then it may be safe to assume the corresponding CMFs are independent and the HSM method applies. If countermeasures target the same crash types, then there is a distinct possibility of dependency and the need for a more nuanced approach.

Logic of Added Benefit versus Fallacy of Additive Effects

Two of the methods presented in Table 1 (Approach 8 and 9) do not consider the effects of multiple treatments. Instead, the method applies a single CMF (e.g., the CMF for the countermeasure with the greatest effect) to estimate the expected reduction in crashes. The primary concern with this method is that it will likely underestimate the potential effects of the project when it is reasonable to assume an added benefit of additional treatments.

While there may be an *added* benefit of applying more than one treatment at a given location, the effects for the treatments are not *additive* because the total crash reduction cannot be greater than 100 percent. Recall the method presented in Approach 1 from Table 1 [$CMF_t = CMF_1 - (1 - CMF_2)/2 - \ldots - (1 - CMF_n)/n$]. While this method reduces the effect of each subsequent treatment by a set amount (i.e., one half, two thirds, etc), the combined effect could exceed 100 percent if enough treatments were implemented or if the expected crash reductions were relatively large for just a few treatments.

Lack of Consistency (Judgment)

Several of the methods presented in Table 1 rely on engineering judgment to determine the appropriate CMF for a combined treatment. While engineering judgment is a necessary component of highway safety, it is also open to interpretation and may result in inconsistencies among or within agencies. CMFs can be used to estimate the expected reduction in crashes, which can then be used as an input in a benefit-cost analysis. If an agency uses the results of benefit-cost analyses (or similar measures) in the allocation of funding, it is important that all divisions within that agency use a consistent method so a fair comparison can be made among projects.

Note that the survey results from Table 1 are relatively dated and the Highway Safety Manual has since been published. Many states may adopt the method for combining CMFs that is outlined in the HSM, thereby partially addressing the problem of inconsistency among states. However, adoption of the HSM method does not address the potential for overestimation of the effects if independence is not established and still incorporates a level of engineering judgment to identify interrelationships among CMFs.

Applicability of CMFs

CMFs may be related to total crashes or specific crash types and/or severities. The crash type and severity associated with a CMF defines the crashes for which the related countermeasure is targeted. It is not appropriate to apply a CMF for a specific crash type or severity to other crash types and severities because a countermeasure may reduce certain crash types or severities while increasing other crash types and severities. Even if multiple treatments are independent, the respective CMFs may be related to different crash types and/or severities. If this is the case, the CMF for a particular crash type and/or severity must only be applied to the crashes expected for that crash type and/or severity. In other words, practitioners should be careful to consider crash type and severity when combining CMFs because simply multiplying the CMFs together without doing so would likely lead to erroneous results.

CMFs are also related to specific roadway and traffic conditions. As discussed in previous resources (*12*), CMFs should not be applied to scenarios for which they do not apply. Examples of specific roadway characteristics include area type, number of lanes, functional classification, and traffic volume.

Lack of Detailed CMF Information

Some agencies are calculating expected reductions by crash type and summing the reductions to estimate project-level benefits. This method is likely to have less overlap than combining CMFs for total crashes, but there is still the risk that multiple treatments will address the same crash type (which relates back to the assumption of independence). For example, a project may be considering shoulder widening and the installation of shoulder rumble strips. Even if the CMFs for the specific crash types are applied separately, the combined effect will likely be over-estimated as the two treatments both address run-off-road crashes. Further, there is the potential that a CMF has not been developed for a specific crash type for a given treatment. In these cases, the agency would not be able to apply a CMF for the specific crash type. There are currently more than 3,000 CMFs in the CMF Clearinghouse, only 1,400 of which are for specific crash types.

Computing a Confidence Interval

A confidence interval provides highly useful information about a parameter. It provides the range of values that contains the parameter with a certain level of probability (e.g., 90%, 95%, or 99%). When working with a CMF, the confidence interval indicates whether a countermeasure has a statistically significant effect on crashes. If the confidence interval includes 1.0, then it can be concluded that the countermeasure does not have a statistically significant effect on crashes with a certain degree of confidence (e.g., 95%). If the confidence interval excludes 1.0, then it can be concluded that the countermeasure does have a statistically significant effect on crashes with a certain degree of confidence. It is, therefore, important to be able to compute a confidence interval for a CMF. A means for computing the confidence interval for multiple CMF estimates for a single countermeasure has been suggested (see Equation 3). However, no method has yet been developed for computing the confidence interval for a CMF estimate of the combined safety effect of multiple countermeasures. There is currently a need for such a method so that users can better estimate the variability of the results.

Exploration of Methods to Overcome Identified Issues

Ideas for Addressing Limitations of Current Methods

Table 2 identifies key factors that need to be addressed to overcome the limitations of current methods for combining multiple CMFs. These factors are explicitly considered in the development of alternative methods in the subsequent section.

TABLE 2. Key Factors to Address Limitations of Current Methods

Issue	Key Factor(s)
Assumption of Independence	• Determine whether or not the assumption of independence is valid for a given scenario. • Identify a consistent method to help users identify potential interrelationships among multiple treatments.
Logic of Added Benefit versus Fallacy of Additive Effects	• Identify the merits and demerits of added benefit in estimating effects of combined treatments. • Create a functional form that does not allow for crash reductions greater than 100 percent when combining multiple CMFs.
Lack of Consistency (Judgment)	• Develop a consistent, quantitative method for identifying interrelationships among multiple treatments. • Provide guidelines for applying engineering judgment to minimize the variance in the process for combining multiple CMFs. • In the absence of a quantitative method for combining multiple CMFs, consider identifying common combinations of treatments. A task group or centralized group within an agency could determine the appropriate CMF to be used for given combinations of CMFs. This list would be provided to the agencies (or divisions within an agency) to promote consistent analysis.

Issue	**Key Factor(s)**
Applicability of CMFs	• Remind users that CMFs are developed for specific scenarios and a CMF should only be applied to applicable scenarios (e.g., area type, functional classification, etc). • Encourage the investigation of individual crash types and severities when possible. • If the CMFs for multiple treatments are related to the same crash type/severity, refer to the first issue, "Assumption of Independence".
Lack of Detailed CMF Information	• Sponsor additional CMF research. • Encourage analysts to investigate treatment effects by individual crash types and severities (in addition to the effect on total crashes).
Computing a Confidence Interval	• Sponsor additional research to explore methods for estimating a combined standard error.

Guidance for Applying Multiple CMFs

Overview

Several existing methods were identified for combining multiple CMFs, and many assume that CMFs are multiplicative. This may be fine provided that the CMFs are 1) independent, and 2) apply to the same crash type. These two principles may seem at odds, but they are really addressing two different issues. The first, independence, relates to the target crash types (i.e., what crashes are expected to be addressed by the treatment). The second principle relates to the general applicability of the CMF (e.g., does the CMF apply to all crashes or specific crash types).

This document first helps CMF users identify interrelationships and determine whether or not the assumption of independence is valid for a specific pair of CMFs. During this step, users also determine the applicable crash types for each CMF. Once the independence is confirmed or rejected and the applicable crash types are defined, the user is guided to an appropriate next step for applying the CMFs.

Identifying Interrelationships and Applicable Crash Types

Interrelationships can be explored through the use of Table 3. This should be the first step of any analysis that combines multiple CMFs. The intent of the matrix is to provide a direct comparison of the target crash types (not to be confused with the applicable crash types of the CMFs). Target crash types are those crashes that a treatment is likely to address/affect. Applicable crash types refers to the applicability of the CMF (some CMFs are applicable to total crashes while others are applicable to specific crash types). The applicability of a CMF depends on the underlying research and crash types included in the analysis. Common crash types are listed along each axis. The steps to using the matrix are as follows:

1. Enter Treatments: The first treatment would be entered along the top of the matrix and the second CMF would be entered along the side of the matrix.
2. Identify Target Crash Types: The user is then responsible for identifying the target crashes for each treatment and indicating these crash types along the respective axes (check the box adjacent to the target crashes). Target crashes may be identified in the NCHRP Report 500 Series (*13*), which lists target crashes for numerous treatments. Target crashes are often listed in research reports as well. Note that some of the "crash types" listed in Table 3 are not mutually exclusive and represent "crash conditions" rather than "crash types." Specifically, "wet pavement" and "night" crashes are listed in Table 3 because some countermeasures explicitly address these types of crashes (e.g., roadway lighting).
3. Identify Interrelationships: Any overlapping crash types (i.e., those crash types targeted by both treatments) can be readily identified and noted in the matrix. For any crash types where there is no overlap, one would expect the full effect of the countermeasure. For those crash types where the treatments overlap, one cannot be certain of the combined effects (i.e., are the actual combined effects less than, equal to, or greater than the

expected combined effects if the CMFs are simply multiplied). The analyst must carefully consider the identified overlaps and select an appropriate course of action. If the two effects are similar (i.e., both CMFs are less than 1.0), the combined effect may be overestimated. If, however, the effects are opposing (i.e., one treatment increases a specific crash type while the other reduces the same crash type), there is the potential to underestimate the combined effect. In particular, there is more opportunity for the second countermeasure to reduce crashes if the first countermeasure is expected to increase the same crash type.

The next step is to identify the applicability of the CMF. CMFs may be applicable to total crashes or to specific crash types. It is not appropriate to apply a CMF for total crashes to specific crash types and vice versa. The applicability of CMFs is discussed in other resources (*12*, *14*).

TABLE 3. Matrix for Comparing Pairs of CMFs

			Target Crash Types for Treatment 1 (check all that apply)														
			Head On	Rear End	Right Angle	Sideswipe Same	Sideswipe Opposite	Left Turn	Right Turn	Fixed Object	Run Off Road	Overturn	Pedestrian	Bicycle	Wet Pavement	Night	Other (Specify)
Target Crash Types for Treatment 2 (check all that apply)		Head On															
		Rear End															
		Right Angle															
		Sideswipe Same															
		Sideswipe Opposite															
		Left Turn															
		Right Turn															
		Fixed Object															
		Pedestrian															
		Bicycle															
		Run Off Road															
		Overturn															
		Wet Pavement															
		Night															
		Other (Specify)															

Identifying an Applicable Scenario

Users should refer to Table 4 to determine next steps based on the interrelationships identified in Table 3 and the applicable crash types. Table 4 identifies six specific scenarios, which are discussed in detail following the table. Scenarios 1 to 3 relate to situations where there are no interrelationships and the standard methods may be used for applying the CMFs. Scenarios 4 to 6 are related to situations where there is overlap between the pair of CMFs. Recall, the combined treatment effect could be greater than, less than, or equal to the simple product of the individual CMFs. Several options are explored for addressing the interrelationships and potential overlap in crash reductions. The alternative methods are listed under the respective scenarios and further detailed in the following section with an applicable example. Note that several of the methods account for potential overestimation, but few consider the potential underestimation of combined treatment effects. In cases where the combined effect of multiple treatments is likely to be greater than the sum of the parts, a user could intentionally select a method that is likely to overestimate the combined effects.

TABLE 4. Identification of Process for Combining Multiple CMFs

Scenario	Interrelationships Identified (Table 3)	Applicable Crash Types (Treatment 1 / Treatment 2)
1	No	Total / Total
2	No	Total / Specific Crash Type(s)
3	No	Specific Crash Type(s) / Specific Crash Type(s)
4	Yes	Total / Total
5	Yes	Total / Specific Crash Type(s)
6	Yes	Specific Crash Type(s) / Specific Crash Type(s)

Scenario 1

In this scenario, there were no interrelationships identified in Table 3. As such the two treatments are assumed to be independent. It is also determined that both CMFs can be applied to total crashes at the location of interest. In this case, the two CMFs can simply be multiplied to determine the combined effect. The combined CMF can then be applied to the total number of expected crashes at the location of interest.

Scenario 2

In this scenario, there were no interrelationships identified in Table 3. As such the two treatments are assumed to be independent. It is also determined that the CMF for one treatment is related to total crashes and the other is related to a specific crash type(s). In this case, it is not appropriate to combine the CMFs by simply multiplying them together because they apply to different crash types. However, the two CMFs are assumed to be independent, so one would expect the full benefit of each treatment. The CMF for total crashes should be applied to the total expected crashes at the location of interest. Separately, the CMF for the specific crash type should be applied to the expected crashes for the given crash type at the location of interest. The expected reductions in crashes can then be summed to estimate the total benefit. The analyst must check to make sure the expected reduction does not exceed the total number of expected crashes. If so, the expected reduction is equal to the total number of expected crashes.

Scenario 3

In this scenario, there were no interrelationships identified in Table 3. As such the two treatments are assumed to be independent. It is also determined that both CMFs apply to different crash types. In this case, it is not appropriate to combine the CMFs by simply multiplying them together because they apply to different crash types. However, the two CMFs are assumed to be independent, so one would expect the full benefit of each treatment. The CMF for treatment #1 should be applied to the expected crashes for the given crash type at the location of interest. Separately, the CMF for treatment #2 should be applied to the expected crashes for the given crash type at the location of interest. The expected reductions in crashes can then be summed to estimate the total benefit. The analyst must check to make sure the expected reduction does not exceed the total number of expected crashes. If so, the expected reduction is equal to the total number of expected crashes.

Scenario 4

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that both CMFs can be applied to total crashes at the location of interest. In this case, the two CMFs cannot simply be multiplied to determine the combined effect because there are likely overlapping effects. There are several existing methods for combining the CMFs for the two treatments as presented in Table 1. There are also several potential variations of the methods presented in Table 1 and others that are yet to be explored. The following methods are explored as part of this effort and described further in the following section with an example.

- 4.1 Assume independence: This method would simply assume the two treatments are independent, regardless of the potential overlap identified in Table 3. The two CMFs would be multiplied to estimate the combined effect. If interrelationships do in fact exist, this method would likely overestimate the combined effect. It is possible, however, that this method could underestimate the combined effect, particularly if the overlapping relationships are opposing.
- 4.2 Apply only the most effective CMF: This method would simply apply the CMF for the most effective treatment. The method is conservative in that it will not likely overestimate the effect of combined treatments if interrelationships do in fact exist. The downside is that this method will underestimate the combined effect if the additional treatments do provide an added benefit.
- 4.3 Systematic reduction of subsequent CMFs: This method assumes the full effect of the first treatment and an added benefit of additional treatments, but not the full effect. This method recognizes that additional treatments are likely to provide an added benefit, but

attempts to account for potential interrelationships. In this way, it is a compromise between the prior two methods. A similar approach could be applied to systematically increase subsequent CMFs if it is expected that the combination of treatments would result in a greater safety benefit than is indicated by the individual CMFs.

4.4 Turner method: This method applies a factor to moderate the effects of the individual CMFs. First the individual CMFs are multiplied together as in Method 4.1 "Assume Independence." Then a factor is applied to the product of the individual CMFs so that the resulting estimate of the combination of countermeasures is brought closer to 1.0. This method was suggested by Turner (*15*) after analyzing different ways to estimate a CMF for a combination of treatments using CMFs of the individual treatments. In the analysis, he compared the estimates from different approaches with CMFs for actual combinations of treatments and found that the estimates consistently overestimated the true crash reductions. That discovery prompted his suggestion of a dampening factor.

4.5 Meta-analysis method: This method applies an approach taken in meta-analysis in which unbiased estimates of the CMF for a particular countermeasure from different studies are combined using Equation 2. The equation makes use of the standard deviation of each CMF estimate. It should be noted that this method was not designed to estimate the combined effect of different countermeasures; rather, it was developed to combine multiple CMF estimates of the same treatment. However, this method is identified as an alternative and applied in this context to combine multiple CMFs for different treatments.

Another potential method is explored in Appendix A with an example to illustrate the application of the method. This method employs meta-analysis techniques and the application of the crash modification function concept to explore the effects of multiple treatments. The method is presented separately in Appendix A because while it shows promise for future investigation, it was difficult to test the method given the general lack of detail provided in many research studies.

Scenario 5

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that the CMF for one treatment is related to total crashes and the other is related to a specific crash type(s). In this case, it is not appropriate to combine the CMFs by simply multiplying them together because they apply to different crash types. Additionally, the two CMFs are NOT assumed to be independent, so one would NOT expect the full benefit of each treatment. The CMF for total crashes should be applied to the total expected crashes at the location of interest. Separately, the CMF for the specific crash type should be applied to the expected crashes for the given crash type at the location of interest. The question now is whether or not the expected reductions in crashes can be summed to estimate the total benefit, or if one or both of the expected reductions should be modified to account for potential overlapping effects. The following method is posed and explained in the following section with an example.

5.1 Apply CMFs separately for total and target crashes: This method first applies the CMF for specific crash types to the expected crashes for that crash type. The CMF for total crashes is then applied to the expected total crashes, but first reducing the total expected crashes by the effect of the CMF for specific crash types.

Scenario 6

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that the CMFs for both treatments apply to a specific crash type(s), which may or may not be the same. In either case, the two CMFs are NOT assumed to be independent, so one would NOT expect the full benefit of each treatment. If the specific crash types are the same for both treatments, the methods from Scenario 4 apply. If the specific crash types are different for the two treatments, the method from Scenario 5 applies. As an alternative, the following method is posed and explained in the following section with an example.

6.1 Apply CMF for most effective treatment to overlapping crash types: This method would apply the CMFs to the respective number of expected crashes (specific crash types). The caveat is that only the most effective CMF would be applied to crash types where there is overlap.

Detailed Methods and Preliminary Assessment

This section presents a detailed discussion, example application, and preliminary assessment of the identified methods. It should be noted that the preliminary assessment is based on specific examples and results may not be applicable to all situations. The premise of the preliminary assessment is a comparison of the results for an individual method (i.e., estimated effect of combined treatment) with the "actual" effect of the combined treatment. The "actual" effect of the combined treatment is also an estimate, but it is based on a study that investigated the combined effect of multiple treatments. This is actually a preferred method for estimating the effects of combined treatments, but few studies of this type have been completed to date.

The examples shown in this section were selected specifically for use in the preliminary assessment. The examples are based on the combination treatment of shoulder widening and installing shoulder rumble strips. It is relatively easy to show that these two treatments target similar crash types and there is likely some overlap in their effectiveness. In addition, CMFs have been developed for the two individual treatments as well as for the combined treatment. In this way, the methods posed in this document are used to estimate the combined effect of the two treatments and the results are then compared to the effect of the combined treatment as estimated through a formal evaluation.

Scenarios 1 to 3 from above are not included in the preliminary assessment as they do not involve the combination of multiple CMFs where there is potential overlap in treatment effectiveness. Scenarios 4 to 6 involve some degree of overlap between the two treatments and specific methods were posed for each scenario. Results from the various methods in Scenarios 4 to 6 are presented and compared to the estimated effects of the combined treatments based on past research. Note that in some cases, there were multiple estimates of the "actual" combined treatment effect identified in the literature.

Scenario 4: Interrelationships with CMF Total / CMF Total

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that both CMFs can be applied to total crashes at the location of interest.

Method 4.1: Assume Independence

Description

Method 4.1 is a commonly used approach to address the issue of applying multiple CMFs when independence is assumed. The method was first proposed by Roy Jorgensen and Associates to estimate an overall CMF from multiple individual CMFs (*16*). This method has since been adopted by the HSM. In this method, Equation 12 is used to compute an overall CMF ($CMF_{combined}$).

$$\mathrm{CMF_{combined}} = \mathrm{CMF_1} * \mathrm{CMF_2} * \ldots * \mathrm{CMF_n} \qquad (12)$$

As shown by the equation, the full benefit of the first countermeasure is assumed. Then for each subsequent countermeasure, the CMF is applied to what remains of the original crashes after the previous CMF has been applied. This method operates on the premise that the safety effect of each countermeasure is independent of the safety effect of every other countermeasure. Consequently, this method ignores the potential interrelationships that exist among the countermeasures.

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17*). Note that both CMFs apply to total crashes and both were based on data from rural, two-lane roads.

Shoulder widening CMF (total crashes) = 0.86 Star Rating: 2

Install shoulder rumble strips CMF (total crashes) = 0.85 Star Rating: 2

The estimated combined CMF from Method 1 is:

$CMF_{combined} = CMF_1 * CMF_2 = 0.86 * 0.85 = 0.73$

Suppose now that the baseline expected total crash frequency (N_{base}) is 10 crashes per mile and the segment of interest is one-mile in length. The expected crash frequency after treatment (N) by Method 4.1 is as follows:

$N = N_{base}(CMF_{combined}) = 10(0.73) = 7.3$ crashes/year.

Method 4.2: Apply Only the Most Effective CMF

Description

Method 4.2 is a highly simple approach to addressing the issue of multiple CMFs. The CMF for only the most effective countermeasure is applied (i.e., lowest CMF value). Thus, with this method, the CMF user would compare the CMF for the first countermeasure with the CMF for the second countermeasure to find and then apply the one with the lowest value.

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17*). Note that both CMFs apply to total crashes and both were based on data from rural, two-lane roads.

Shoulder widening CMF (total crashes) = 0.86 Star Rating: 2

Install shoulder rumble strips CMF (total crashes) = 0.85 Star Rating: 2

The estimated combined effect from Method 4.2 is simply the CMF from the treatment with the greater effect. The more effective CMF is the one with the lowest value.

The CMF for installing shoulder rumble strips has a lower value (0.85) compared to the CMF for shoulder widening (0.86). As such, the combined CMF is assumed to be 0.85. Suppose now that the baseline expected total crash frequency (N_{base}) is 10 crashes per mile and the segment of interest is one-mile in length. The expected crash frequency after treatment (N) by Method 4.2 is as follows:

$N = N_{base}(CMF_{combined}) = 10(0.85) = 8.5$ crashes/year.

Method 4.3: Systematic Reduction of Subsequent CMFs

Description

Method 4.3 is similar to Method 1 in Table 1 in that the effect of the second countermeasure is systematically diminished. It differs in that a multiplicative approach is taken instead of an additive approach. In this method, the CMF user would first identify the more effective of the two countermeasures (i.e., the CMF with the lower value). Then the user would reduce the second CMF according to Equation 13.

$$\text{CMF}_{2,\text{Reduced}} = \frac{1-\text{CMF}_2}{2} + \text{CMF}_2 \quad (13)$$

The estimated combined effect from Method 4.3 is the product of CMF_1 and $CMF_{2,\ Reduced}$ as given in Equation 14.

$$CMF_{combined} = CMF_1 * CMF_{2,Reduced} \quad (14)$$

Note that the expected effectiveness of the second treatment is reduced by a factor of two. This is based on the premise of Method 1 identified in Table 1, but there is no theoretical basis for this factor. There are likely merits to this method (i.e., a systematic reduction of subsequent CMFs), but there is clearly a need for future research to refine the specific reduction.

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17*). Note that both CMFs apply to total crashes and both were based on data from rural, two-lane roads.

Shoulder widening CMF (total crashes) = 0.86 Star Rating: 2

Install shoulder rumble strips CMF (total crashes) = 0.85 Star Rating: 2

To apply Method 4.3, the user must first identify the less effective CMF. In this case, shoulder widening (CMF = 0.86) is expected to be slightly less effective than shoulder rumble strips (CMF = 0.85). It is then necessary to reduce the estimated effect of the second CMF as follows:

$$\text{CMF}_{2,\text{Reduced}} = \frac{1-\text{CMF}_2}{2} + \text{CMF}_2 = \frac{1-0.86}{2} + 0.86 = 0.93$$

The estimated combined effect from Method 4.3 is then the product of CMF_1 and $CMF_{2,\ Reduced}$.

$CMF_{combined} = CMF_1 * CMF_{2,Reduced} = 0.85 * 0.93 = 0.79$

Suppose now that the baseline expected total crash frequency (N_{base}) is 10 crashes per mile and the segment of interest is one-mile in length. The expected crash frequency after treatment (N) by Method 4.3 is as follows:

$N = N_{base}(CMF_{combined}) = 10(0.79) = 7.9$ crashes/year.

Method 4.4: Turner Method

Description

After an analysis of different methods for combining multiple CMFs using New Zealand data, Turner (*15*) discovered that all methods overestimate the crash reduction and developed a rule of thumb in an attempt to correct the problem. Turner suggests a factor of two-thirds be applied to the product of multiple CMFs to dampen the crash reduction as given by Equation 15.

$$\mathrm{CMF_{combined}}[\text{Turner Method}] = 1 - \left[\frac{2}{3}\left(1 - (\mathrm{CMF_1} * \mathrm{CMF_2})\right)\right] \tag{15}$$

As with Method 4.3, more research is needed to provide justification for the use of this factor. It was developed from limited data exclusively from New Zealand. Therefore, the general applicability of this factor or any single factor for that matter remains questionable.

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17*). Note that both CMFs apply to total crashes and both were based on data from rural, two-lane roads.

Shoulder widening CMF (total crashes) = 0.86 Star Rating: 2

Install shoulder rumble strips CMF (total crashes) = 0.85 Star Rating: 2

Using the Turner method, the combined CMF would be estimated as follows:

$$\mathrm{CMF_{combined}}[\text{Turner Method}] = 1 - \left[\frac{2}{3}\left(1 - (\mathrm{CMF_1} * \mathrm{CMF_2})\right)\right] = 1 - \left[\frac{2}{3}\left(1 - (0.86 * 0.85)\right)\right]$$

$$\mathrm{CMF_{combined}}[\text{Turner Method}] = 0.82$$

Suppose now that the baseline expected total crash frequency (N_{base}) is 10 crashes per mile and the segment of interest is one-mile in length. The expected crash frequency after treatment (N) by Method 4.4 is as follows:

$N = N_{base}(CMF_{combined}) = 10(0.82) = 8.2$ crashes/year.

Method 4.5: Meta-Analysis Method

A method for combining CMFs for the same countermeasure from different studies was previously given. To reiterate, this method uses a weighted average of the individual CMFs, using the standard error of the estimates in the weighting as shown in Equation 16 (*7*).

$$\mathrm{CMF} = \frac{\sum_{i=1}^{n} \mathrm{CMF_{unbiased,i}}/S_i^2}{\sum_{i=1}^{n} 1/S_i^2} \tag{16}$$

This method is designed to place greater weight on the individual CMF with the smaller standard error. An estimate of the standard error for the combined CMF can be computed by Equation 17 (*7*).

$$S = \sqrt{\frac{1}{\sum_{i=1}^{n} 1/S_i^2}} \quad (17)$$

Although this method was not originally intended to combine CMFs for different treatments, it is of interest to know how it compares relative to the other approaches outlined above.

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17*). Note that both CMFs apply to total crashes and both were based on data from rural, two-lane roads. It should also be noted that the CMFs used in the other methods of Scenario 4 cannot be used directly for this method because the original study and the CMF Clearinghouse do not provide standard errors (S_i) for the respective CMFs. However, it was possible to approximate the standard errors using the methods suggested by Bahar (*7*) and the crash summary data presented in the original study (*17*). The estimated standard error for Treatment 1 (shoulder widening) is 0.057 and the estimated standard error for Treatment 2 (installing shoulder rumble strips) is 0.073.

Shoulder widening CMF (total crashes) = 0.86 (S_i = 0.057) Star Rating: 2

Install shoulder rumble strips CMF (total crashes) = 0.85 (S_i = 0.073) Star Rating: 2

Using Method 4.5, the combined CMF would be estimated as follows:

$$CMF = \frac{\sum_{i=1}^{n} CMF_{unbiased,i}/S_i^2}{\sum_{i=1}^{n} 1/S_i^2} = \frac{\frac{0.86}{0.057^2} + \frac{0.85}{0.073^2}}{\frac{1}{0.057^2} + \frac{1}{0.073^2}} = 0.86$$

$$S = \sqrt{\frac{1}{\sum_{i=1}^{n} 1/S_i^2}} = \sqrt{\frac{1}{\frac{1}{0.057^2} + \frac{1}{0.073^2}}} = 0.045$$

Suppose now that the baseline expected total crash frequency (N_{base}) is 10 crashes per mile and the segment of interest is one-mile in length. The expected crash frequency after treatment (N) by Method 4.5 is as follows:

$N = N_{base}(CMF_{combined}) = 10(0.86) = 8.6$ crashes/year.

Assessment of Scenario 4 Methods

Table 5 compares the estimated and actual combined treatment effects based on the methods presented in Scenario 4. Recall that Scenario 4 applies to situations where there are interrelationships between two treatments and both related CMFs are applicable to total crashes.

As shown above, each of these methods estimated a CMF for a combination of treatments (shoulder widening and installing shoulder rumble strips) using the CMFs for the individual treatments. These estimates now can be compared to CMFs from literature for the actual combination of treatments.

A comparison of the estimated and actual combined CMFs reveals that Method 4.1 and Method 4.3 produce results that are within the range of the estimated effects from actual studies of the combined treatment. In this particular instance, Method 4.1 and Method 4.3 appear to provide a reasonable estimate of the combined treatment effect since they fall within the range of actual combined CMF values. The combined CMF from Method 4.2 falls outside the range of actual combined CMF values and is closer to 1.0 than both estimates from the actual studies of the combined treatment. As discussed previously, Method 4.1 has a tendency to over-estimate the crash reduction, Method 4.2 has a tendency to underestimate the crash reduction, and Method 4.3 has a tendency to produce estimates that fall between those of the other two methods. Based on this example, these tendencies are apparent when comparing the results from the first three alternative methods.

It is difficult to generalize the tendencies of Method 4.4 and Method 4.5. In this example, the combined CMFs from Method 4.4 and Method 4.5 fall outside the range of actual combined CMF values and are closer to 1.0 than both estimates from the actual studies of the combined treatment. In both cases, the method tempers the expected reduction from the individual CMFs, but may underestimate the combined effect as shown in this example.

TABLE 5. Comparison of Estimated and Actual Combined Treatment Effect (Scenario 4)

Method	Estimated Combined CMF	Actual Combined CMF (*Source*)
4.1 Assume Independence	0.73	0.63 (*17*)[1] 0.81 (*18*)[1]
4.2 Apply Only Most Effective CMF	0.85	
4.3 Systematic Reduction of Subsequent CMFs	0.79	
4.4 Turner Method	0.82	
4.5 Meta-Analysis Method	0.86	

1. CMF applies to total crashes.

Scenario 5: Interrelationships with CMF Total / CMF Specific

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that the CMF for one treatment is related to total crashes and the other is related to a specific crash type(s).

Method 5.1: Apply CMFs Separately for Total and Target Crashes

Description

Method 5.1 applies a multi-step procedure for estimating the expected combined effect of two countermeasures. First, the CMF for the countermeasure that targets specific crash types is applied to the expected crashes for that crash type. This product is then used to compute the expected reduction in crashes due to that countermeasure. The reduction in crashes for the specific crash type would then be subtracted out from the total expected crashes for the location of interest. Finally, the CMF for the countermeasure that targets total crashes would be applied to the remaining total expected crashes (after subtracting out the expected reduction from the first treatment).

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*17, 19*). Note that the CMFs were obtained from two different studies, and the applicability of the CMFs does not exactly match with respect to crash type and area type. Specifically, the CMF for shoulder widening applies to total crashes while the installation of shoulder rumble strips applies to run-off-road crashes. While both CMFs were developed using data from two-lane roads, one may also argue that the CMFs do not apply to the same area type. The authors did not specify the applicable area type for the CMF for shoulder widening. As such, it is assumed that the CMF applies to all area types. The CMF for installing shoulder rumble strips is applicable to rural area types. Whether or not these two CMFs are directly applicable to a given roadway is a question that practitioners face on a regular basis. In the context of this illustration, the slight inconsistency is not important as the purpose is to demonstrate how to combine one CMF (i.e., shoulder widening) which applies to total crashes and another CMF (i.e., installing shoulder rumble strips) that targets a specific crash type (i.e., run-off-road).

Shoulder widening CMF (total crashes) = 0.86 Star Rating: 2

Install shoulder rumble strips CMF (run-off-road crashes) = 0.74 Star Rating: 4

Suppose now that the baseline expected total crash frequency ($N_{base, Total}$) is 10 crashes per mile per year, the baseline expected run-off-road crash frequency ($N_{base, ROR}$) is 4 crashes per mile per year, and the segment of interest is one-mile in length. It should be noted that models to predict the crash frequency for target crash types may not be available. For instance, the HSM provides safety performance functions (SPFs) to estimate the expected total crash frequency for various roadway types, but it does not provide SPFs for specific crash types. Instead, the HSM presents alternative methods for estimating the baseline expected crash frequency for target crashes (e.g., crash type distribution to estimate proportion of total crashes represented by a specific crash type). In this case, the crash history of the roadway was used to estimate the proportion of target crashes (i.e., 40 percent of total crashes are run-off-road).

In Method 5.1, the CMF for the specific crash type is first applied to the expected crash frequency of the specific crash type to estimate the expected crashes (of the given crash type) after treatment (N_{ROR}):

$N_{ROR} = N_{base, ROR}$*CMF(shoulder rumble strips) = 4*0.74 = 2.96 crashes/year

The expected reduction in the target crash type is then as follows:

$N_{base, ROR} – N_{ROR} = 4 – 2.96 = 1.04$ crashes/year

The reduction in target crashes is then subtracted from the expected total crash frequency:

$N_{base, Total, Reduced} = N_{base, Total} – (N_{base, ROR} – N_{ROR}) = 10 – 1.04 = 8.96$ crashes/year

The CMF for total crashes is then applied to the reduced expected crashes to obtain the final estimate of the combined treatment effect on total crashes ($N_{combined}$):

$N_{combined} = N_{base, Total, Reduced}$*CMF(shoulder widening) = 8.96*0.86 = 7.71 crashes/year

Back-calculating the combined CMF for total crashes based on the result from Method 5.1 would result in a combined CMF of 0.77. Note that a different CMF would result if the assumed baseline expected run-off-road crashes ($N_{base, ROR}$) was changed. This is further explored through a sensitivity analysis where combined CMFs are back-calculated assuming different proportions of target crashes. Specifically, the potential range in the combined CMF is shown, assuming 10 percent of total crashes are run-off-road and again assuming 90 percent of total crashes are run-off-road.

$CMF_{combined} = 0.84$ (assuming target crash type is 10 percent of total crashes)

$CMF_{combined} = 0.66$ (assuming target crash type is 90 percent of total crashes)

There is a wide range in the potential value of the combined CMF based on the assumed proportion of target crashes. This indicates a potential weakness of the method, but also illustrates that the proportion of target crashes can influence the expected effect of the combined treatment.

Assessment of Scenario 5 Method

Table 6 compares the estimated and actual combined treatment effects for shoulder widening and shoulder rumble strips based on Scenario 5. Recall that Scenario 5 applies to situations where there are interrelationships between two treatments and one CMF is applicable to total crashes while the other CMF is applicable to specific crash types. Note that two of the "actual" combined effects in Table 6 are based on total crashes while the third is based on run-off-road crashes. As such, these estimates only provide an approximation of the effects that could be expected from the combination of the CMF for shoulder widening (total crashes) and the CMF for shoulder rumble strips (run-off-road crashes).

A comparison of the estimated and actual combined CMFs reveals that Method 5.1 produces results that are in the range of the estimated effects from actual studies of the combined treatment. In this particular instance, Method 5.1 appears to provide a reasonable estimate of the combined treatment effect. Note that a different estimated CMF would result if the assumed baseline expected run-off-road crashes ($N_{base, ROR}$) was changed as shown in the earlier example.

Notably, the results of the sensitivity analysis still fall within the range of the CMFs from actual studies.

TABLE 6. Comparison of Estimated and Actual Combined Treatment Effect (Scenario 5)

Method	Estimated Combined CMF	Actual Combined CMF (*Source*)
5.1 Apply CMFs Separately for Total and Target Crashes	0.77	0.63 (*17*)[1] 0.81 (*18*)[1] 0.87 (*18*)[2]

1. CMF applies to total crashes.
2. CMF applies to run-off-road crashes.

Scenario 6: Interrelationships with CMF Specific / CMF Specific

In this scenario, there were interrelationships identified in Table 3. As such the two treatments are NOT assumed to be independent. It is also determined that the CMFs for both treatments are related to specific crash types, which may or may not be the same.

Note: If the specific crash types are the same for both treatments, the methods from Scenario 4 apply. If the specific crash types are different for the two treatments, the method from Scenario 5 applies. As an alternative, method 6.1 is posed if there is overlap among the target crashes for the two treatments. For a description and illustration of methods from Scenario 4 and Scenario 5, refer to the above sections.

Method 6.1: Apply CMF for Most Effective Treatment to Overlapping Crash Types

Description

In Method 6.1, the user would apply the CMFs to the respective number of expected target crashes (specific crash types). The key to this method is that only the most effective CMF would be applied to crash types where there is overlap. If the expected crashes after treatment (N) is the product of N_{base} and the applicable CMF, and N_{base} is composed of multiple crash types (A, B, and C), it can be shown by the distributive property that:

$$N = N_{base} * CMF = (A + B + C) * CMF = A*CMF + B*CMF + C*CMF$$

Now assume that CMF_1 is for the more effective treatment and applies to target crash types A, B, and C, while CMF_2 is for the less effective treatment and applies to target crash types C, D, and E. The expected target crashes for the two treatments are as follows:

$$N_{base1} = A + B + C$$

$$N_{base2} = C + D + E$$

Using the logic from above, the user could apply the CMF for treatment 1 to the expected target crashes for treatment 1 (A, B, and C) to estimate the expected crashes after treatment (N_1).

Similarly, the user could apply the CMF for treatment 2 to the expected target crashes for treatment 2 (C, D, and E) to estimate the expected crashes after treatment (N_2).

$N_1 = N_{base1} * CMF_1 = (A + B + C)*CMF_1 = A*CMF_1 + B*CMF_1 + C*CMF_1$

$N_2 = N_{base2} * CMF_2 = (C + D + E)*CMF_2 = C*CMF_2 + D*CMF_2 + E*CMF_2$

In this scenario, there is overlap between the two treatments in that they both target crash type C. Applying Method 6.1, the expected effect on any overlapping crash types (in this case crash type C) would be based only on the treatment with the greatest effect. In this case, the expected crashes after treatment (N) would be the following:

$N = N_1 + N_2(\text{minus overlap}) = A*CMF_1 + B*CMF_1 + C*CMF_1 + D*CMF_2 + E*CMF_2$

The expected reduction in target crashes based on the combined effect of treatments 1 and 2 is then calculated as follows:

$N_{base,\ Total} – N = [A + B + C + D + E] – N$

Illustration

This example illustrates the combination of CMFs for two treatments on a rural, two-lane road. Treatment 1 is shoulder widening and treatment 2 is installing shoulder rumble strips. CMFs were identified from the CMF Clearinghouse for the two individual treatments (*20*,*19*). Note that the CMF for shoulder widening applies to head-on (HO), run-off-road (ROR), and opposite direction sideswipe (OppSS) crashes (*20*) and the installation of rumble strips applies to ROR crashes for this scenario (*19*). Both CMFs were based on data from rural, two-lane roads.

Shoulder widening CMF (HO, ROR, OppSS crashes) = 0.86 Star Rating: 3

Install shoulder rumble strips CMF (ROR crashes) = 0.74 Star Rating: 4

Suppose now that the segment of interest is one-mile in length and the baseline expected target crash frequencies are as follows for HO, ROR, and OppSS crashes:

$N_{base,\ HO}$ = 2 crashes per mile per year

$N_{base,\ ROR}$ = 6 crashes per mile per year

$N_{base,\ OppSS}$ = 1 crashes per mile per year

In this case, the user would then estimate the expected crashes after treatment (N_1) by applying the CMF for shoulder widening to head-on and opposite direction sideswipe crashes. Note there is overlap for treatments 1 and 2. Specifically, they both target run-off-road crashes. The CMF for shoulder widening is not applied to run-off-road crashes because the CMF for shoulder rumble strips is more effective and will be applied separately to this overlapping crash type.

N (shoulder widening) = N_{base1} * CMF_1 = (N $_{base, HO}$ + N $_{base, OppSS}$)*CMF_1 = (2+1)*0.86

N (shoulder widening) = 2.58 crashes/year

N (shoulder rumble strips) = N_{base2} * CMF_2 = (N $_{base, ROR}$)*CMF_2 = 6*0.74

N (shoulder rumble strips) = 4.44 crashes/year

In this case, the expected crashes after treatment (N) would be the following:

N = N (shoulder widening) + N (shoulder rumble strips) = 2.58 + 4.44 = 7.02 crashes/year

The expected reduction in target crashes based on the combined effect of treatments 1 and 2 is then calculated as follows:

$N_{base, Total}$ – N = [2 + 6 + 1] – 7.02 = 1.98 crashes/year

Back-calculating the combined CMF for target crashes based on the result from Method 6.1 would result in a combined CMF of 0.78. Note that a different CMF would result if the assumed baseline expected crashes were changed. This is again explored through a sensitivity analysis where combined CMFs are back-calculated assuming different numbers of target crashes. Specifically, the potential range in the combined CMF is shown, assuming one run-off-road crash and again assuming nine run-off-road crashes.

$CMF_{combined}$ = 0.83 (assuming one run-off-road crash)

$CMF_{combined}$ = 0.77 (assuming nine run-off-road crashes)

There is a relatively small range in the potential value of the combined CMF based on the assumed number of target crashes for which the CMFs overlap. This is a potential weakness of the method, but also illustrates that the number of target crashes can influence the expected effect of the combined treatment.

Assessment of Scenario 6 Method

Table 7 compares the estimated and actual combined treatment effects for shoulder widening and shoulder rumble strips based on Scenario 6. Recall that Scenario 6 applies to situations where there are interrelationships between two treatments and both related CMFs are applicable to specific crash types, which may or may not be the same for the two treatments. Note that the “actual” combined effect in Table 7 is based on run-off-road crashes. As such, this estimate only provides an approximation of the effects that could be expected from the combination of the CMF for shoulder widening (head-on, run-off-road, and opposite direction sideswipe crashes) and the CMF for shoulder rumble strips (run-off-road crashes).

At first glance, it appears that Method 6.1 may over-estimate the combined effect compared to the estimated effects from an actual study of the combined treatment. However, it should be noted that there is only one comparison point and the estimated combined CMF includes the effects on head-on, run-off-road, and opposite direction sideswipe crashes, while the actual effect is only for run-off-road crashes. As such, it may be reasonable to assume that the CMF would be slightly more effective when accounting for the effects on additional crash types. In this particular instance, Method 6.1 appears to provide a reasonable estimate of the combined treatment effect. Note that a different estimated CMF would result if the assumed baseline expected target crashes were changed as shown in the earlier example.

TABLE 7. Comparison of Estimated and Actual Combined Treatment Effect (Scenario 6)

Method	Estimated Combined CMF	Actual Combined CMF (*Source*)
6.1 Apply CMF for Most Effective Treatment to Overlapping Crash Types	0.78	0.87 (*18*)[1]

1. CMF applies to run-off-road crashes.

Appendix A presents an additional method that was explored as part of this research. While the method shows promise for future investigation, it was difficult to test using available data. As such, results are not presented in Tables 5 – 7 for this method. Instead, the method is described with an example in Appendix A.

Conclusions and Future Research

The most rigorous approach for estimating the effects of multiple treatments is to install combination treatments and estimate a CMF for the combination. There has been limited research to date that considers the effects of multiple treatments. While there is ongoing research to further develop CMFs for common combination treatments (e.g., combination treatments at signalized and unsignalized intersections as part of the FHWA Evaluation of Low-Cost Safety Improvements Pooled Fund Study), there is still a need to estimate the combined effects of other treatments.

Several existing methods were identified for combining multiple CMFs. Each method was reviewed and the associated issues were identified. The primary issue with existing methods is the assumption of independence when combining CMFs, which can lead to over- or underestimation of the combined treatment effect. Other issues include 1) the logic of an added benefit versus the fallacy of additive effects, 2) the lack of consistency when applying methods, 3) the general applicability of CMFs, 4) a lack of detailed information to apply the specific methods, and 5) the lack of a method to estimate a confidence interval for the combined CMF of multiple treatments.

A framework was developed for investigating interrelationships between two treatments and identifying the applicability of related CMFs. In this document, it is suggested that no more than two CMFs be combined in an analysis. In the case of three or more countermeasures, one may encounter a scenario in which the net combined effect of the countermeasures approximately equals the product of the individual countermeasures, but only because of offsetting effects (i.e., it is possible that two of the three countermeasures account for the vast majority of the reduction). A matrix is provided to help identify potential overlapping effects between two treatments, but it is the responsibility of the analyst to determine how these interrelationships will play out.

Six distinct scenarios were identified based on the interrelationships of treatments and the applicability of the related CMFs. An attempt was then made to identify alternative methods for estimating the combined effects of multiple treatments, considering the limitations of current methods. It is important to note that different methods apply to different scenarios. Several current and alternative methods were presented with examples to illustrate each method. Many of the methods account for potential overestimation, but few consider the potential underestimation of combined treatment effects. The emphasis on avoiding overestimation seems justified based on the limited research literature that exists on the topic. In a 2005 study, Mounce assessed the accuracy of the multiplicative approach (referred to as Method 4.1 in this document) and discovered that it overestimates the actual reduction in a majority of instances (*21*). Further, an analysis of combination treatments in New Zealand assessed the accuracy of multiple methods for combining CMFs, and it was concluded that all methods reviewed in the effort overestimate the crash reduction (*15*). Nonetheless, analysts should be aware of the potential to underestimate the combined treatment effect. Case in point, Method 4.2 in Table 5 shows how the estimated crash reduction for shoulder widening and installing shoulder rumble strips can be less than the actual value. In any case, engineers should be equally concerned about overestimation and underestimation because both would lead to incorrect decisions about whether or not to apply a particular countermeasure.

Data were then obtained from the CMF Clearinghouse in an attempt to compare and assess the existing and proposed methods. Method 4.1 (Assume Independence) and Method 4.3 (Systematic Reduction of Subsequent CMFs) produce results that are in the range of the estimated effects from actual studies of the combined treatment. Method 4.1, however, appears to overestimate the combined effect when compared to Method 4.3. The estimated combined CMFs from Method 4.2 (Apply Only Most Effective CMF), Method 4.4 (Turner Method), and Method 4.5 (Meta-Analysis Method) are outside the range of actual combined CMF values and are closer to 1.0 than both estimates from the actual studies of the combined treatment. As such, these methods appear to underestimate the combined treatment effect. Method 5.1 (Apply CMFs Separately for Total and Target Crashes) and Method 6.1 (Apply CMF for Most Effective Treatment to Overlapping Crash Types) appear to provide reasonable estimates of the combined treatment effect; however, the CMFs estimated from these two methods were based on a very specific scenario with assumed expected crashes. It was shown that different assumptions for the expected crashes would lead to a different estimate of the combined treatment effect.

This document has provided a review of existing methods for combining CMFs for multiple treatments and explored alternative methods. While several existing and alternative methods were compared, this study provides only a starting point for future research in this area. The preliminary assessment of methods indicated positive results, but there is still a tremendous amount of work to be done, including a more rigorous and large scale effort to investigate the combination of multiple CMFs and a method to estimate a confidence interval for the combined CMF. Notably, there is a need to test the existing and proposed methods in a controlled experiment and with several different treatments to further explore their validity and potential weaknesses. Method 4.3 (Systematic Reduction of Subsequent CMFs) appears to hold promise for combining multiple CMFs, but there is a need to determine a more formal and rigorous method for computing the reduction of the second CMF. There is also a need to explore a variation of Method 4.3 where the effect of a subsequent treatment is increased to account for potential underestimation of the combined treatment. Method 5.1 and Method 6.1 illustrate that the proportion of target crashes can influence the combined CMF. This is an important area for future research. Another area in need of investigation is the combination of CMFs when they apply to different severities. Finally, there is a need to convey the importance of complete and consistent reporting to CMF researchers so that methods such as the one proposed in Appendix A can be further explored.

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Appendix A: Exploration of an Alternative Method for Combining CMFs

Application of Meta-Analysis and Crash Modification Functions

One potential method for applying multiple CMFs may be to use the crash modification function development process proposed by Elvik (*9*) in conjunction with the CMF Clearinghouse. Recall that the process outlined by Elvik sought to identify systematic variations in CMF values as a function of some characteristic(s). In his proposed process, those characteristic(s) may or may not be directly relatable to countermeasure(s). The intent was to bring to light any trends in safety performance as a function of one or more independent variables. In order to address the issue of applying multiple CMFs, his process would have to be adapted such that the characteristics (i.e., the independent variables) would need to be directly relatable to countermeasure(s). A process adapted from Elvik's work is proposed below and consists of the following steps:

1. Selection of Countermeasures of Interest.
2. Specification of CMF Information within the CMF Clearinghouse.
3. Identification of CMFs Associated with Countermeasures of Interest.
4. Regression Analysis for Identified CMFs.
5. Verification of Regression Analysis
6. Computation of Final CMF Value.

Each step is described in below:

1. Selection of Countermeasure of Interest

The proposed process begins with the selection of two sets of countermeasures: the primary countermeasure and secondary countermeasure(s). The primary countermeasure is the countermeasure that is of greatest interest (i.e., thought to be the most effective) to the CMF user. For instance, the primary countermeasure may be to change the width of a roadway located along a horizontal curve to determine the impact on the frequency of fixed object crashes. Secondary countermeasure(s) are roadway characteristics that may affect the safety effectiveness of the primary countermeasure. Continuing with the previous example, a secondary countermeasure may be to increase the clear zone along the horizontal curve. Clear zone certainly has an effect on the frequency of fixed object crashes along horizontal curves but its effect is likely smaller than that of roadway width. The CMF user can use the CMF Clearinghouse to confirm or reject his or her intuition on the relative importance of countermeasures. More specifically, the user can examine and compare the magnitude of CMF values for the countermeasures of interest.

At this stage in the process, the CMF user should also consider the crash types that are targeted by the countermeasures. If the primary and secondary countermeasures do not have overlapping target crash types, then the assumption of independence may hold. If the assumption of independence is true, the HSM method (i.e., multiplying the CMFs) would be valid, and the rest of this proposed process need not be followed. If the assumption of independence becomes questionable after comparing the target crash types, then the CMF user should continue with the proposed process.

2. Specification of CMF Information within the CMF Clearinghouse

Once primary and secondary countermeasures have been selected, the CMF user would then go to the CMF Clearinghouse and search for CMFs by inputting critical information. What constitutes *critical* will depend on the situation. Although the CMF Clearinghouse allows users to search for CMFs using a large array of parameters (e.g., countermeasure, crash type, severity, roadway type, and area type), specifying information for too many parameters may be counterproductive. The purpose of this step of the process is to produce a sizeable number of CMF search results from which further analysis will be possible. Specifying too many parameters in the query may defeat this purpose since too few search results may be produced. Therefore, some engineering judgment is required at this stage to find the appropriate level of specificity. At a minimum, the countermeasure, crash type, and severity level should be specified. In the case of many but not all countermeasures, roadway type and area type also need to be specified. Other fields may also be necessary depending on the countermeasures involved.

3. Identification of CMFs Associated with Countermeasures of Interest

The next step in the process involves sifting through the search results of CMFs for the primary countermeasure to identify CMFs that are associated with the secondary countermeasure(s). This step may require multiple approaches.

Approach 1: This approach involves scanning through countermeasure names within the search results to find references to the secondary countermeasure(s). In the case of some CMF studies, the CMF is computed with a secondary countermeasure in mind. For example, the primary countermeasure may be to change lane width assuming a certain shoulder width. The countermeasure name may be “increase lane width of roadway with 4 ft. shoulders from 11 ft. to 12 ft.” Another countermeasure name may be “increase lane width of roadway with 6ft. shoulders from 11 ft. to 12 ft.” Note that, when identifying CMFs, the values for the primary countermeasure (e.g., increasing lane width from 11 ft. to 12 ft.) must be the same while the values of the secondary countermeasure (e.g., 4 ft. shoulder and 6 ft. shoulder) must differ.

Approach 2: This approach involves scanning through the “prior conditions” field of the CMF results. In the CMF Clearinghouse, the “prior conditions” refers to the “condition of the road or intersection before the countermeasure was implemented” (*22*). In some cases, the secondary countermeasure may be found there. For instance, the countermeasure may be increasing lane width by 1 ft. and the prior conditions may be a “roadway with 11 ft. lanes and 6 ft. shoulders.” Another CMF entry may have the same countermeasure name but the prior conditions may be a “roadway with 11 ft. lanes and 4 ft. shoulders.”

Using one or both approaches, the CMF user could compile a list of CMFs that account for both the primary and secondary countermeasures.

4. Regression Analysis for Identified CMFs

After compiling the list of CMFs, the next step is to run a regression analysis to identify trends within the selected results. This step may be performed by plotting the point estimates from the search results and finding the best fitting curve or line to the points. The confidence interval for each of the point estimates should also be plotted so the standard error of each estimate is taken into account. Elvik (*9*) provides two demonstrations by plotting CMF values from the literature as a function of an independent variable. In the first instance, he was successful at generating an intuitive crash modification function for the construction of bypass roads in Norway in which the independent variable was population. In the second instance, he was unsuccessful at generating an intuitive crash modification function for the conversion of intersections to roundabouts as a function of roundabout diameter. His work indicates that it may be difficult to identify intuitive trends in every instance.

In many cases, it is a challenge to identify enough CMF entries to produce intuitive results (i.e., the sample size is too small). It is also telling that that no attempt was made to construct a multivariate (i.e., two or more independent variables) crash modification function. Identifying trends for a multivariate crash modification function would be even more difficult than for a univariate crash modification function. It still would be helpful to plot CMF values to identify trends for a multivariate crash modification function. The plot would consist of a three-dimensional graph with the independent variables on the x and y axes and the CMF value on the z axis.

5. Verification of Regression Analysis

Once the regression analysis has been conducted to produce a trend line that best fits the plot of CMF values, the trend line needs to be validated. Validation can be done by plotting additional CMF values from the same study or another study with the same study design and then checking whether these new points conform to the trend line. Whether the new data points conform to the trend line or not, the trend line needs to be revised to incorporate the new data points. If the new data points largely conform to the existing trend line, then the revision should be minor (e.g., slight change in intercept or coefficients). If the new data points do not conform to the existing trend line, then the revision may be major. For instance, the addition of new data points may suggest a different functional relationship (e.g., linear, exponential, logarithmic, polynomial) than was originally thought. Alternatively, the additional data points may be completely at odds with the existing trend line and suggest no clear relationship whatsoever. In this situation, it is possible that, contrary to initial expectations, the implementation of the secondary treatment has no effect on the safety performance of the primary countermeasure. In other words, the assumption of independence should be reconsidered in that scenario.

6. Computation of Final CMF Value

The last step is to obtain a final CMF estimate for the implementation of multiple treatments. If the previous step of verifying the trend line is successful, this step should be straightforward. In such a case, this step would simply be a matter of interpolating a CMF value using the revised best fit curve developed in the previous step.

Example Application of Crash Modification Functions

A demonstration of the proposed process for developing crash modification functions using an adaptation of Elvik's methodology and the CMF Clearinghouse may be instructive.

1. Selection of Countermeasures of Interest

The process begins with the selection of the primary and secondary countermeasures of interest. Suppose that a CMF user were interested in examining the safety effects of converting an intersection from yield control to signal control while accounting for the safety effects of changing the density (i.e. signals per mile) of signalized intersections. In this case, the two countermeasures of interest are 1) the conversion of intersection traffic control from yield to stop, and 2) the alteration of signalized intersection density. In this case, the CMF user considers the former to be the primary countermeasure and latter to be the secondary countermeasure.

2. Specification of CMF Information within the CMF Clearinghouse.

The CMF user then utilizes the CMF Clearinghouse to search for CMF entries that match the countermeasures of interest. The user may begin by specifying the countermeasure category: intersection traffic control. Then the user may specify the target crash type and severity level: all crashes types and all severity levels. In this example, area type would be another important parameter since urban and rural intersections have different crash characteristics (e.g., crash rates and severity levels). Suppose in this case that urban intersections are of interest. Lastly, the number of legs is also a critical parameter, because it affects the crash characteristics at the intersection (e.g., number of conflict points). Suppose that in this case four-legged intersections are of interest. After inputting these parameters, the CMF Clearinghouse returns 62 CMFs.

3. Identification of CMFs Associated with Countermeasures of Interest.

From the results that were returned, the CMF user must identify the entries associated with the countermeasures of interest. Recall that there were two approaches to this step, 1) examination of the countermeasure names, or 2) examination of the prior conditions. First the countermeasure names were examined, and four CMF entries were identified:

I. Convert from yield control to signal control (intersection crashes with signal more than 500 m away).
II. Convert from yield control to signal control (intersection crashes with 1 signal 200-500 m away).
III. Convert from yield control to signal control (intersection crashes with 2 signals 200-500 m away).
IV. Convert from yield control to signal control (intersection crashes with 1-2 signals under 200 m away).

It is noteworthy that, in this example, all four entries were from the same study (*23*). Therefore, depending on the CMF results, this method may or may not be a meta-analysis. These CMFs account for both the primary and secondary countermeasures of interest: conversion of an intersection from yield control to signal control and changing signal density. An examination of the other entries using the prior conditions field did not yield any further pertinent CMFs. Note that these results meet the requirement that the primary countermeasure not change (i.e., conversion from yield control to signal control) while the values for the secondary countermeasure change (e.g., 0 signals within 500 m, 1 signal within 500 m).

4. Regression Analysis for Identified CMFs.

After compiling the list of appropriate CMF entries, the regression analysis can be conducted. The CMF values for the identified entries need to be plotted to discern any trends. Prior to plotting the values, a unit conversion is necessary in this case so that signal density is given in terms of signals per mile. Note that, for the fourth data point, an average was computed from the range of 1 to 2 signals under 200 m (i.e., 1.5 signals was assumed). Table 1 shows the converted values along with the corresponding CMF values and confidence intervals.

TABLE 1. Conversion of Countermeasures to Signal Density

Countermeasure	Signal Density (signals per mile)	CMF	Lower 95% Confidence Limit	Upper 95 % Confidence Limit
I. 0 signals within 500 m	0.00	0.72	0.42	1.21
II. 1 signal within 500 m	3.22	0.66	0.47	0.93
III. 2 signals within 500 m	6.44	0.59	0.38	0.92
IV. 1.5 signals within 200 m	12.07	0.52	0.35	0.78

CMF values are then plotted. Not all the entries should be plotted because a portion of the data needs to be reserved for validation. With only four data points, it is logical to set aside one data point for validation. One data point was selected at random to serve as the validation point, the data point for Countermeasure III. Figure 1 shows the CMF values plotted as diamond points for different signal densities. Of all the possible trend lines, a straight line proved to have the highest coefficient of determination (i.e., R^2). It appears that there is a linear relationship between the CMF values for the primary countermeasure (i.e., converting from yield to signal control) as a function of the secondary countermeasure (i.e., existing signal density). The crash modification function produced from the regression analysis is given by the following equation:

CMF(conversion from yield to signal control) = 0.717 – (0.0164 * Signal Density)

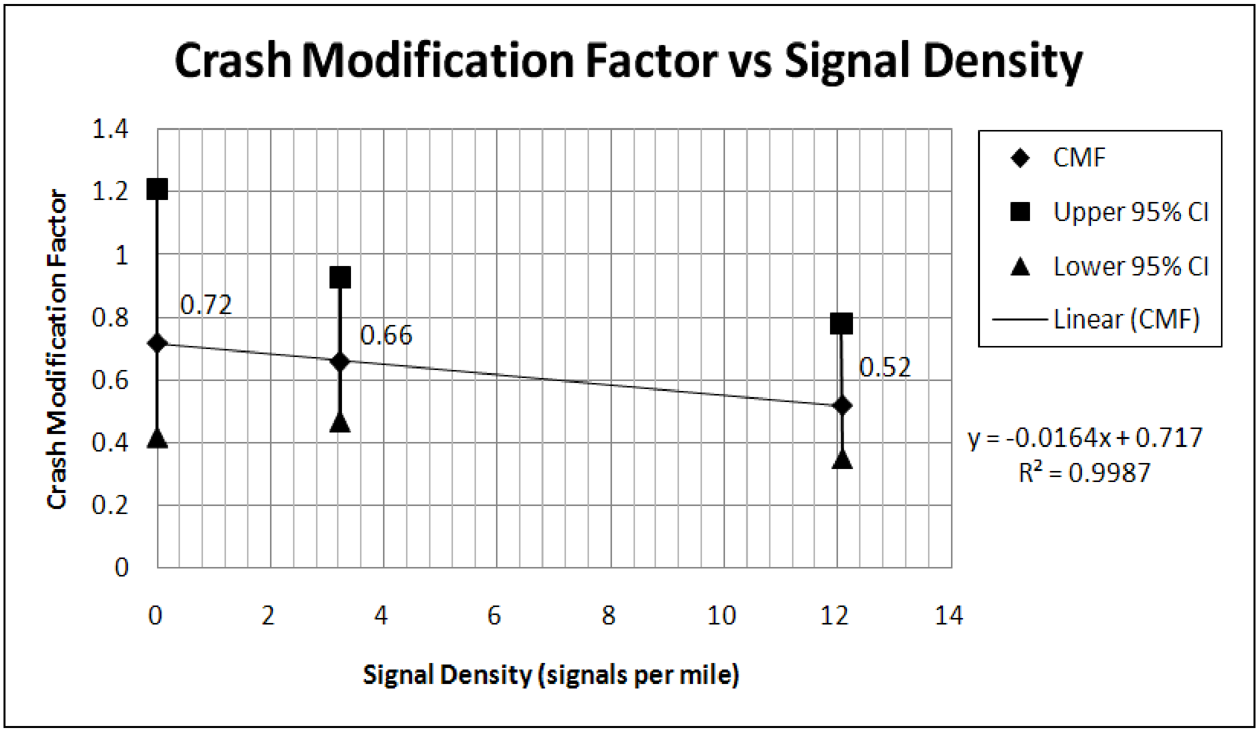

FIGURE 1. Crash Modification Function for the Conversion from Yield to Signal Control as a Function of Existing Signal Density

5. Verification of Regression Analysis

Verifying the regression analysis requires the use of the validation data. The validation data point is shown in Figure 2. According to the crash modification function, the expected crash modification factor for converting yield to signal control with a signal density of 6.44 signals per mile would be as follows:

CMF(Signal Density=6.44) = 0.717 – (0.0164*6.44) = 0.61

This projection is fairly close to the actual crash modification factor reported by the study (0.59). The trend line produced from the regression analysis appears to be verified.

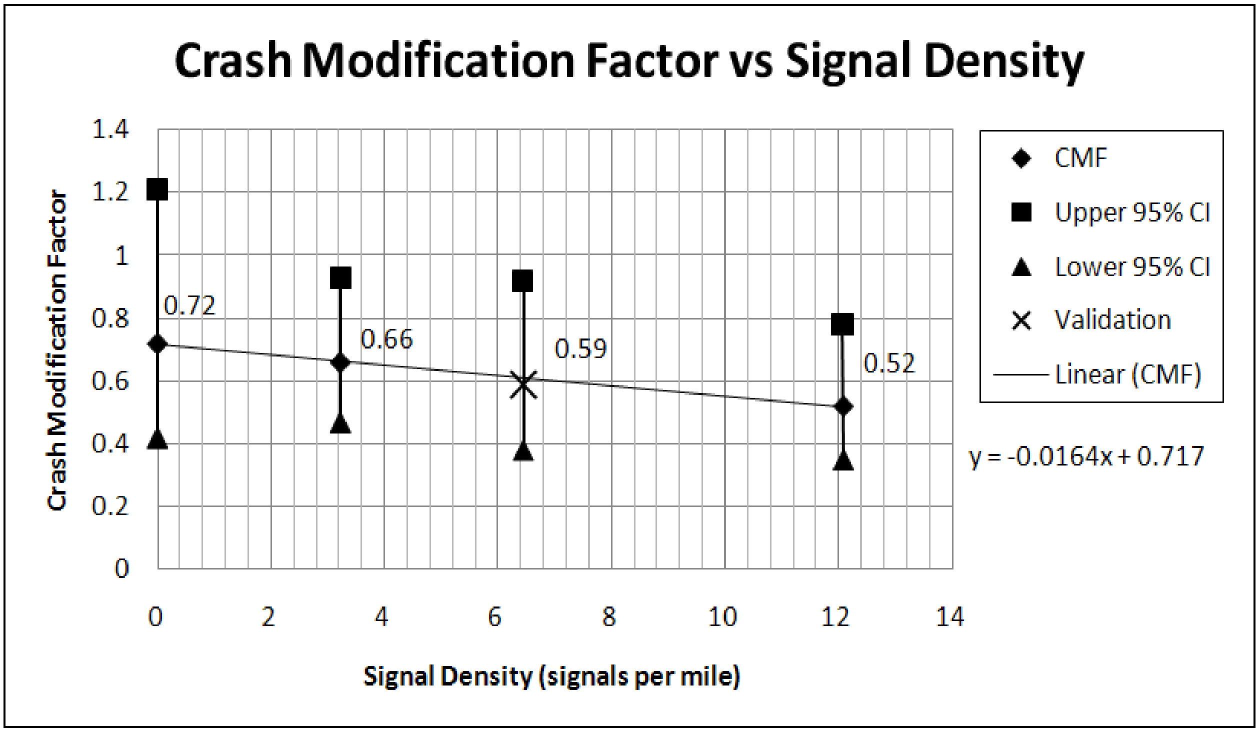

FIGURE 2. Crash Modification Function for the Conversion from Yield to Signal Control as a Function of Existing Signal Density with Validation Data

6. Computation of Final CMF Value.

The last step in this demonstration is to obtain a CMF value using the results of the regression analysis. Since a trend line was successfully constructed and verified in previous steps, this step merely consists of interpolating a value from the best fit line. Suppose that the CMF user is seeking an estimated CMF for the conversion of an intersection from yield control to signal control while accounting for the effect of signal density. Assuming the existing signal density is two signals per mile, the estimated crash modification factor would be as follows:

CMF(conversion from yield control to signal control) = -0.0164(2) + 0.717 = 0.68.

Applicability of Method

This method of developing crash modification functions with the CMF Clearinghouse has great potential but limited applicability given the current level of detail provided in many research studies. It attempts to account for the interrelationships that may exist between countermeasures but can only be applied in certain circumstances (i.e., when detailed information are provided for the circumstances surrounding a given evaluation). At the very beginning, the user must already have in mind which secondary countermeasure(s) affects the safety effectiveness of the primary countermeasure. Further, data on both the primary and secondary countermeasures must be available within the CMF Clearinghouse. Often a study that examines one countermeasure does not consider the secondary countermeasure. Moreover, even when multiple CMF entries are available, the regression analysis may not prove successful. Consider the example of Elvik's roundabout conversion meta-analysis (*9*). No clear trend may be discernable from the CMF entries possibly due to lack of a sufficient quantity of high quality studies.