APPENDIX B

Procedure for Estimating the Combined Safety Effect of Two Treatments

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B.1. Introduction

Crash modification factors and functions (CMFs) provide users with an opportunity to quantify the safety performance of their decisions. In some cases, a transportation agency will apply multiple treatments to a location, such as signalizing a stop-controlled intersection, adding turn lanes, and reducing intersection skew. The preferred approach to estimate the combined safety effect of multiple treatments is to apply a single CMF that represents the combined treatments. In the absence of such a CMF, practitioners need to know how to apply CMFs that represent individual treatment effects to estimate the combined safety effect.

This guidance presents a recommended method to estimate the combined safety effect of **two treatments at the same location**. While the guidance can be used to estimate the effects of more than two treatments, this study was unable to assess the accuracy of methods to combine more than two individual CMFs.

The target audience for this guidance is those who develop and apply CMFs to quantify the safety performance of design decisions or contemplated safety treatments. These users may include highway designers, traffic engineers, transportation planners, and highway safety analysts and researchers.

The guidance begins with an overview of methods to estimate the combined safety effect of multiple treatments. Continue reading for a background on the application of multiple CMFs or skip to section B.2 for the procedure on applying single-effect CMFs to estimate the combined safety effect of two treatments. Examples in section B.3 illustrate how users can apply CMFs to estimate the joint safety effect of two treatments.

Section B.2 discusses how to extend the method to estimate the combined safety effect of more than two treatments, but readers should note the lack of research to verify the accuracy of combining more than two individual CMFs.

Methods to Estimate the Combined Safety Effect of Multiple Treatments

Table B1 provides a summary of the following five methods for estimating the combined safety effect of multiple treatments. Note that not all methods combine individual CMFs. For example, the Dominant Effect for Overlapping Crash Types method applies CMFs separately to applicable crash types and severities, and then aggregates the results to estimate the combined effect.

1. Dominant Effect Method
2. Additive Effects Method
3. Multiplicative Method
4. Dominant Common Residuals Method
5. Dominant Effect for Overlapping Crash Types

Table B1. Summary of Existing Methods for Estimating Combined Effects

Method	Summary of Method
Dominant Effect	The dominant effect method applies the CMF for only the most effective treatment (i.e., lowest CMF value). This method is a simplified and conservative approach to estimating the combined effect of multiple treatments. By only applying a single CMF, this method avoids the issue of independence. The primary limitation of this method is that it is likely to underestimate the combined treatment effect if subsequent treatments improve safety.

Method	Summary of Method
Additive Effects	The additive effects method assumes that CMFs are independent, and estimates the combined effect by adding the individual effects as follows: $\mathrm{CMF_t} = 1 - [(1 - \mathrm{CMF_1}) + (1 - \mathrm{CMF_2}) + \cdots + (1 - \mathrm{CMF_n})]$ (1) $\mathrm{CMF_t}$ = CMF for the combined treatments $\mathrm{CMF_1}$ = CMF for the most effective treatment $\mathrm{CMF_2}$ = CMF for the second most effective treatment $\mathrm{CMF_n}$ = CMF for the n^{th} most effective treatment The primary limitation of this approach is that the combined effect could exceed 100 percent if enough treatments are added or if the estimated crash reductions are relatively large for just a few treatments. Another limitation is that it may not be appropriate if the treatment effects are not independent (i.e., when there are overlapping effects). Readers should note that this method adds the *effects*, not the CMFs themselves.
Multiplicative	The multiplicative method assumes that CMFs are independent, and estimates the combined effect by multiplying the individual CMFs as follows: $\mathrm{CMF_t} = \mathrm{CMF_1} * \mathrm{CMF_2} * \ldots * \mathrm{CMF_n}$ (2) All terms as defined previously. This is the most common method at this time, and is identified in the Highway Safety Manual (AASHTO, 2010). The primary limitation of this method is that the combined effect may be underestimated or overestimated if the treatment effects are not independent.
Dominant Common Residuals	This method, proposed by Elvik (2009), is similar to the multiplicative method, except the non-independent CMFs (i.e., common residuals) are raised to the power of the most effective CMF (i.e., dominant common residual). The combined effect of multiple treatments is estimated as follows: $\mathrm{CMF_t} = (\mathrm{CMF_1} * \mathrm{CMF_2} * \ldots * \mathrm{CMF_n})^{CMF_1}$ (5) All terms as defined previously. The primary limitation of this method is that there is no theoretical justification. However, it does provide a more conservative estimate of the combined effect than the multiplicative method (i.e., common residuals methods) as noted by Elvik (2009). Another limitation is when the individual CMFs are greater than 1.0, particularly the most effective treatment. In these cases, the combined CMFs are raised to a power greater than 1.0, which intensifies the effect rather than dampening. As such, this method is not appropriate for CMFs greater than 1.0.

Method	Summary of Method
Dominant Effect for Overlapping Crash Types	This method applies the CMF for only the most effective treatment (i.e., lowest CMF value) where there is overlap among the treatment effects. Otherwise, the CMFs are applied separately to the target crashes. In a standard CMF application, the estimated number of crashes without treatment, N_{wo}, is multiplied by a CMF to estimate the number of crashes with treatment, N_w. If N_{wo} is comprised of multiple crash types (e.g., A + B + C), then each crash type can be multiplied by the CMF separately: $N_w = N_{wo} * CMF$ $N_w = (A + B + C) * CMF$ $N_w = A*CMF + B*CMF + C*CMF$ Consider the combined effect of two treatments, with one more effective than the other. CMF_1 is associated with the more effective treatment and applies to crash types A and B. CMF_2 is associated with the less effective treatment and applies to crash types B and C. Therefore, the applicable crashes for the two treatments are as follows: $N_{wo,1} = A + B$ $N_{wo,2} = B + C$ CMF_1 is applied to $N_{wo,1}$ (A+B) to estimate the crashes with treatment one ($N_{w,1}$). CMF_2 is applied to $N_{wo,2}$ (B+C) to estimate the crashes with treatment two ($N_{w,2}$). $N_{w,1} = N_{wo,1} * CMF_1 = (A + B)*CMF_1 = A*CMF_1 + B*CMF_1$ $N_{w,2} = N_{wo,2} * CMF_2 = (B + C)*CMF_2 = B*CMF_2 + C*CMF_2$ Following this logic, $N_{w,1}$ and $N_{w,2}$ could be combined to estimate N_w; however, there is an overlap in addressing crash type B. This method accounts for overlap by using only the most effective CMF for any overlapping crash types. In this case, the estimated crashes with both treatments, N_w, is computed as follows, omitting $B*CMF_2$: $N_w = A*CMF_1 + B*CMF_1 + C*CMF_2$ This method accounts for potential overlapping treatment effects, but the primary limitation is that it may be difficult to identify the specific crashes that overlap between treatments.

Background on the Application of Multiple CMFs

The key factors to consider when applying multiple CMFs include:

1. Selection of appropriate CMFs.
2. Application of CMFs by type and severity.
3. Bounds of combined treatment effect.
4. Overlapping effects among individual treatments.
5. Magnitude of individual treatment effects.

Selecting an Appropriate CMF

The CMF selection process involves several considerations including availability of CMFs, applicability of available CMFs, and quality of applicable CMFs. The key to selecting an appropriate CMF is to identify the CMF that best matches the scenario at hand. The following is an overview of CMF availability, applicability, and quality. Readers can refer to the CMF Clearinghouse for more information (www.cmfclearinghouse.org). The CMF Clearinghouse is a web-based database of CMFs that includes supporting documentation to help users identify, select, and apply appropriate CMFs.

Availability of CMFs

The Highway Safety Manual (AASHTO, 2010) and CMF Clearinghouse (FHWA, 2016) are the two primary sources of CMFs.

Applicability of CMFs

CMFs are applicable to specific crash types, severities, and roadway conditions. It is important for the user to identify the applicable crash types, severities, and roadway conditions of each CMF, and only use CMFs for the conditions to which they apply. Several variables define the applicability of a CMF including treatment type, roadway type, area type, segment or intersection geometry, segment or intersection traffic control, traffic volume, and state from which the CMF was developed. The HSM and CMF Clearinghouse provide information to help users decide which CMFs are most applicable to a given situation.

Quality of CMFs

If multiple applicable CMFs exist for a given treatment, then the quality or standard error can be used to differentiate the results. The CMF Clearinghouse provides quality ratings for CMFs which may be used for this purpose. In the absence of a quality rating, users may compare CMFs by their standard error where a smaller standard error indicates a greater level of certainty for a CMF estimate.

Applying CMFs by Type and Severity

CMFs apply to specific crash types and severities. It is often useful to estimate the change in crashes by crash type and severity, but this should only be done when there are CMFs available for the specific crash types and severities in question. It is inappropriate to apply a CMF for a specific crash type and severity to another crash type and severity. For example, consider a CMF for installing a traffic signal at a two-way stop-controlled intersection. If the CMF applies to the net effect (all crash types and severities combined), then it is inappropriate to apply the CMF to estimate the individual effect on angle and rear-end crashes because the individual effects are not likely equivalent to the net effect of the treatment. In this example, a traffic signal may reduce angle crashes and increase rear-end crashes.

Considering the Bounds of the Combined Treatment Effect

In estimating the combined effect of multiple treatments, it is important to recognize the potential bounds of the treatment effects. This will serve as a reality check when applying the methods in this guidance. In reality, the bound for the maximum effect of one or more treatments is 100 percent (a CMF of 0). This condition represents the complete elimination of crashes. The lower bound is more difficult to establish. In theory, there is no limit on the minimum reduction in crashes, and this reduction can even be negative (i.e., an increase in crashes). In practice, one may assume a minimum reduction of zero (i.e., no benefit) if the objective is to improve safety. In this case, it is assumed that analysts would eliminate treatments from consideration if the treatment is likely to increase crashes. There are other scenarios where practitioners may be interested in quantifying the combined effect of features that may increase crashes (e.g., design exceptions or comparing negative impacts of reducing program budgets). As such, analysts should consider the specific scenario, and determine the bounds of potential combined effects.

Considering the Overlap among Individual Treatments

Another consideration is the overlap among individual treatments. Specifically, two or more treatments may complement, replace, or counteract each other. The analyst must apply judgment to determine the likelihood and extent of overlap among estimated effects of the contemplated treatments, and select an appropriate method to estimate the combined safety effect. The NCHRP Report 500 series of guides may be helpful in judging the overlap of treatment effect, since they provide guidance on identifying the target crash types for individual safety treatments (AASHTO, 2003-2009).

The following is general guidance to assess the potential overlap among individual treatments, followed by five specific categories for use with this guidance. It is necessary to consider the conditions and location in the context of potential overlapping treatment effects. Conditions are defined by setting (road type or intersection type), crash type (severity, manner of collision), time period (day/night), and traffic volume (if specified). Location describes the portion of the road to which the treatment is being applied (e.g., outside lane in one travel direction, curves on two-lane highway with a radius of 400 to 500 feet, one approach of a signalized intersection). The following two cases describe different levels of overlap among treatments based on the associated condition and location.

- **Case 1—Same Condition and Same Location**: If the CMFs are all defined for the same condition and the associated treatment is applied to the same location, then they are more likely to be highly related (i.e., likely to affect the same crashes). For example, two CMFs associated with treatments that target rear-end crashes resulting in injury during daytime hours on the northbound approach of a rural, stop-controlled intersection are likely to have a high degree of overlap as they will affect the same crashes.
- **Case 2—General Conditions and Non-Specific Locations**: If the CMFs are all defined for general conditions and non-specific locations (e.g., overall segments, overall intersection), then the degree to which they are related will be difficult to quantify. For example, consider two CMFs that are both quantified in terms of their effect on total intersection crashes, and the associated treatments are applied to separate intersection approaches. The effect of an approach-specific treatment on total intersection crashes is an extrapolation of the treatment's approach-specific effect that generalizes the unspecified conditions of the untreated intersection approaches.

Engineering judgment is critical to determine if each treatment is likely to affect specific conditions and whether these conditions overlap. Similarly, engineering judgment is used to determine if the associated treatments interact when they are applied at relatively distant locations (e.g., an adjacent segment). The related CMFs are more likely to interact when they have more conditions in common, or the treatment influences the same drivers at the same (or a nearby) location.

Case A: Zero Overlap in Treatment Effect

This case represents two truly independent effects. For example, consider a scenario where motorcycle and pedestrian crashes represent 40 percent and 20 percent of total crashes, respectively. If the first treatment reduces motorcycle crashes by 50 percent and the second treatment reduces pedestrian crashes 50 percent, then the combined effect is a 30 percent reduction in total crashes.

Case B: Some Overlapping Treatment Effects

This case represents scenarios between Case A and Case C (i.e., the overlapping effect is between 0 and 100 percent). In this case, the second treatment provides some additional benefit, but the full effect of the second treatment is not realized due to overlap with the first treatment. For example, consider a scenario where there are 2.0 cross-median crashes and 4.0 run-off-road crashes per year on a four-lane, median divided facility. The two treatments considered are cable median barrier and shoulder rumble strips on the inside and outside shoulders. If the cable barrier reduces cross-median crashes by 50 percent and the rumble strips reduce cross-median and run-off-road crashes by 50 percent, then the estimated reduction is between 3.0 crashes per year (i.e., no additional benefit from rumble strips) and 3.5 (i.e., full effect of rumble strips). This case includes an inherent interaction effect because the second treatment can only reduce the crashes that remain after considering the effects of the first treatment. For example, if the first treatment reduces total crashes by 30 percent, then only 70 percent of crashes remain for the second treatment.

Case C: Complete Overlap in Treatment Effects

This case represents two non-independent effects where the second treatment targets some or all of the same crash types and severities as the first treatment. For example, widening both the lane and shoulder width may target the same run-off-road, head-on, and opposite direction sideswipe crashes. If this is the case, then the effect is equal to the CMF associated with the dominant treatment.

Case D: Enhancing Treatment Effects

This case represents a scenario where the combined effect of two treatments is greater than the sum of their individual effects. While you cannot reduce crashes by more than 100 percent, it is possible that two treatments could interact to enhance the combined effect. For example, installing rumble strips in conjunction with shoulder widening may be more effective than the product of the individual CMFs for rumble strips and shoulder widening because the added shoulder provides recovery room for drivers alerted by the rumble strips.

Case E: Counteracting Treatment Effects

This case represents a scenario where the combined effect of two treatments is less than the effect of the most effective treatment. In this case, the second treatment may counteract the effect of the first treatment or vice versa. This is a common scenario in the evaluation of design exceptions. For example, a highway designer may consider installing advance curve warning signs to offset the potential impacts of reducing the radius of a curve due to topographical constraints.

Magnitude of Individual Treatment Effects

Depending on the magnitude of the individual treatment effects, the method selected to estimate the combined safety effect may have a nominal or significant impact on the final result. Table B2 presents sample CMFs representing small and large individual effects along with the estimate of the combined safety effect based on four of the five methods from Table B1. A CMF value of 0.95 is used to represent a small effect (i.e., a five percent reduction) and a CMF of 0.70 is used to represent a large effect (i.e., a 30 percent reduction). These two CMF values have been combined using the various methods to show a comparison of methods within each column of Table 2.

When both individual treatment effects are small, the four methods produce similar estimates of the combined effect, ranging from 0.90 to 0.95 (a difference of 0.05). When one treatment effect is small and the other is large, there is more variability in the estimates of the combined effect from the four methods. Specifically, the results range from 0.65 to 0.75 (a difference of 0.10). When both individual treatment effects are large, there is even more variability in the estimates of the combined effect from the four methods. Specifically, the results range from 0.40 to 0.70 (a difference of 0.30). It is clear from Table B2 that the magnitude of the individual treatment effects has a bearing on the importance of the method selected to estimate the combined treatment effect. In particular, it is critical to select an appropriate method when both individual treatment effects are large; otherwise, there is potential to severely over- or underestimate the combined treatment effect.

Table B2. Sample CMFs Illustrating Importance of Magnitude of Effect

Method	Combined Effect (small-small)	Combined Effect (small-large)	Combined Effect (large- large)
Dominant Effect = CMF1 (largest effect)	0.95	0.70	0.70
Additive Effects = 1 – [(1 – CMF1) + (1 – CMF2)]	0.90	0.65	0.40
Multiplicative = CMF1*CMF2	0.90	0.67	0.49
Dominant Common Residuals = (CMF1*CMF2)^CMF1	0.91	0.75	0.61

General Guidance for Estimating the Combined Safety Effect of Two Treatments

This research indicates that no one method for combining safety effects of two treatments outperforms the others in all cases. However, to promote implementation, it is appropriate for practitioners to use the following guidance when the CMFs for two treatments apply to the same crash types and severities (in absence of the four-step process shown in Figure B1 and discussed in the following section). When CMFs apply to different crash types and severities, practitioners should follow the recommendations in the following section.

1. When both CMFs are less than 1.0, the Dominant Common Residuals method generally performs best (i.e., is the most accurate) across all scenarios.
2. When one or both CMFs are greater than 1.0, the Dominant Effect method generally performs best across all scenarios.
3. In most cases, the Dominant Effect method provides the most conservative estimate of treatment benefits and is appropriate for use in estimating the combined safety effects for single projects. This is true for typical safety projects where both CMFs are less than 1.0. Practitioners should use caution when comparing the results of the Dominant Effect method between projects as the method is likely to inconsistently underestimate the effects of different treatment combinations.

Some methods perform much better than this abbreviated guidance in specific scenarios, and following the recommendations in the previous section will provide the most consistently accurate results for estimating the effects of treatment combinations.

B.2. Procedure

This procedure is intended to guide the decision process for selecting the most appropriate method to estimate the combined effect of two treatments. Figure B1 is a flowchart that illustrates the steps of the procedure. The decision process is based on three key factors: potential overlap of individual treatment effects, magnitude of individual treatment effects, and the applicability of the individual CMFs. Following the figure and related tables, there is a more detailed description of the process, including examples to illustrate how to navigate the decision process and then how to apply the methods. The remainder of this section assumes two treatments have been identified for potential application, CMFs are available for the individual treatments in question, and the analyst would like to estimate the combined effect of the treatments.

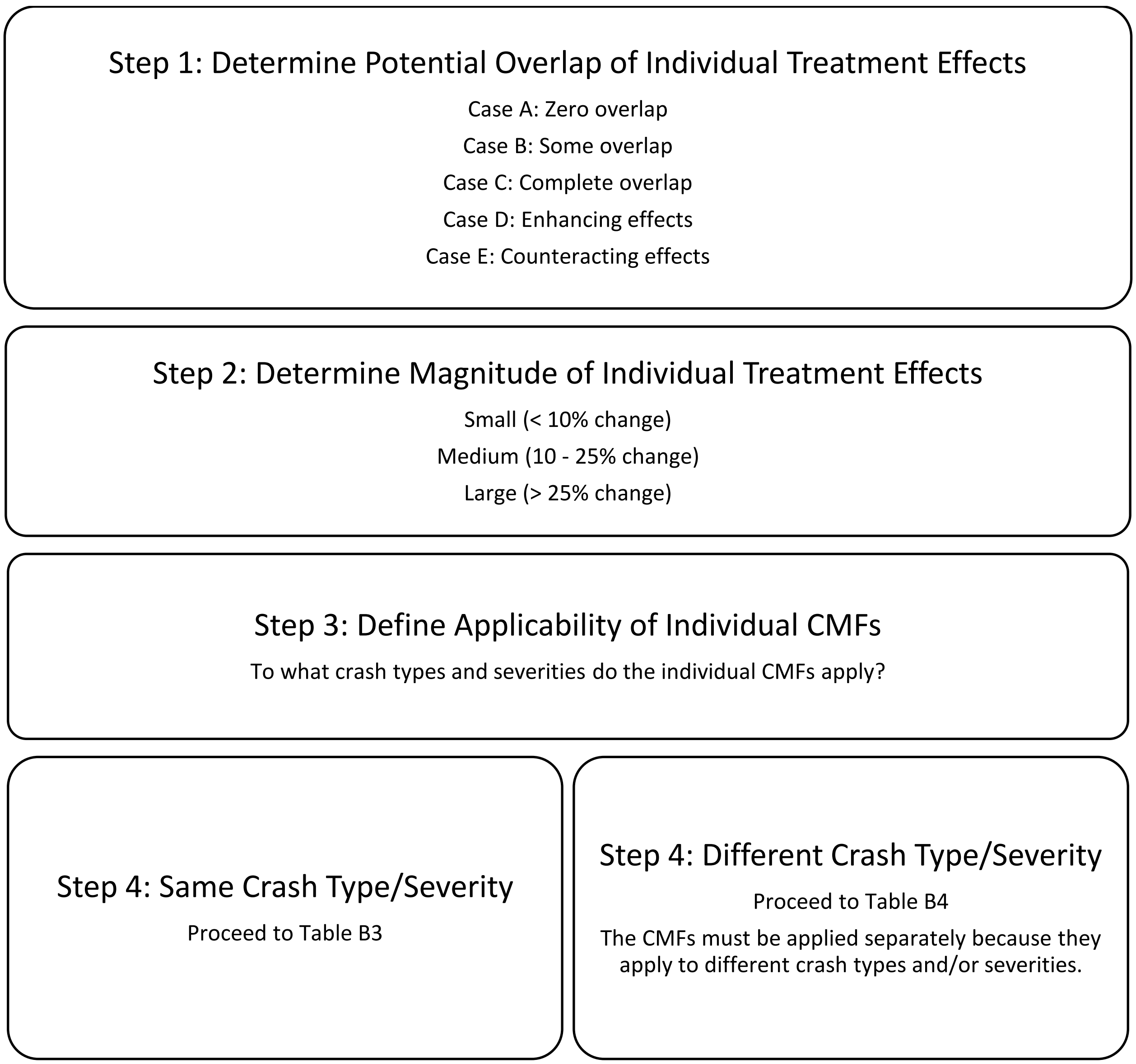

Figure B1. Flow Chart for Selecting Appropriate Method for Combining CMFs for Two Treatments

Table B3. Method Selection for Same Crash Type and Severity

Overlap	Magnitude	Method
Case A Case D	Not applicable	Additive effects with maximum reduction of 100% (i.e., CMF = 0)
Case B	Small-Small	Dominant effect
	Small-Medium	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Small-Large	Dominant effect
	Medium-Medium	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Medium-Large	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
	Large-Large	Dominant common residuals (if CMFs < 1.0); Dominant effect otherwise
Case C	Not applicable	Dominant effect
Case E	Not applicable	Multiplicative

Table B4. Method Selection for Different Crash Type and Severity

Overlap	**Method**
Case A Case D	*Additive Effects with Maximum Reduction of 100% (i.e., CMF = 0).* Assuming no overlap among treatment effects, one would expect the full benefit of each treatment. 1. Apply the CMF for the first treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 3. Sum the estimated change in crashes to calculate the net effect. 4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.
Case B Case E	*Dominant Effect for Overlapping Crash Types* Assuming some overlap among the treatment effects, one would expect the full benefit of the most effective treatment and some additional benefit from the second treatment. 1. Apply the CMF for the most effective treatment (i.e., the lowest CMF) to the estimated crashes without treatment for the applicable crash type/severity at the location of interest. 2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest, excluding crashes associated with the most effective treatment. 3. Sum the estimated change in crashes to calculate the net effect. 4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.
Case C	*Dominant Effect* Assuming complete overlap among the treatment effects, one would expect the full benefit of only the most effective treatment. Note that this is a simplified version of Case B. 1. Apply the CMF for the most effective treatment (i.e., the lowest CMF) to the estimated crashes without treatment for the applicable crash type/severity at the location of interest.

The following is a detailed description of the decision process presented in Figure B1. To set-up an example that continues through the discussion, assume that an analyst is considering two treatments, centerline and shoulder rumble strips, to address safety concerns related to head-on and run-off-road crashes. Table B5 presents the CMFs and applicability of the CMFs for the individual treatments.

Table B5. CMFs for Centerline Rumble Strips Only and Shoulder Rumble Strips Only

Treatment	CMF	Applicable Crash Type	Applicable Crash Severity	Applicable Roadway Characteristics	Source
Install centerline rumble strips	0.912	Run-off-road, head-on, and sideswipe	All	Urban and rural, two-lane, undivided roads	NCHRP 17-63
Install shoulder rumble strips	0.844	Run-off-road, head-on, and sideswipe	All	Urban and rural, two-lane, undivided roads	NCHRP 17-63

At this point, the analyst has identified two treatments for potential application, and CMFs are available for the individual treatments in question. Given this information, the analyst can proceed to estimate the combined effect of the treatments.

Step 1: Determine Potential Overlap of Individual Treatment Effects

The first step is to determine the potential overlap of the individual treatment effects. As discussed in the B.1. subsection titled, *Considering the Overlap among Individual Treatments*, two or more treatments may complement, replace, or counteract each other. The analyst must determine the likelihood and extent of overlap among the contemplated treatments, and select the category from Table B6 that best matches the scenario at hand.

Table B6. Defining the Overlap of Individual Treatment Effects

Case	Description
A: Zero overlap	This case represents two truly independent effects where the complete benefit of both treatments is realized.
B: Some overlap	This case represents two treatments that both provide some level of benefit, but the second treatment has some overlap with the first.
C: Complete overlap	This case represents two non-independent effects where the second treatment targets some or all of the same crash types/severities as the first.
D: Enhancing effects	This case represents a scenario where the combined effect of two treatments is greater than the sum of their individual effects because one treatment enhances the effectiveness of the other treatment.
E: Counteracting effects	This case represents a scenario where the combined effect of two treatments is less than the effect of the most effective treatment because one treatment counteracts the effect of the other treatment.

Continuing with the example from above, the two treatments are installing centerline rumble strips and shoulder rumble strips. Centerline rumble strips target head-on, sideswipe opposite direction, and run-off-road left crashes, but may affect other crash types such as run-off-road right. Shoulder rumble strips target run-off-road right crashes, but may affect other crash types such as head-on, sideswipe opposite direction, and run-off-road left. This suggests that there is likely some overlap among the treatments, which corresponds to Case B from Table B6.

Step 2: Determine Magnitude of Individual Treatment Effects

The second step is to determine the magnitude of the individual treatment effects based on the levels defined in Table B7. If both individual treatment effects are small (i.e., less than 10 percent change), there is relatively little difference between the methods. As the magnitude of effect increases, the methods produce much different estimates, and it becomes more important to select an appropriate method.

Table B7. Defining the Magnitude of Individual Treatment Effects

Individual Effect	Assigned Magnitude
< 10% change	Small
10 – 25% change	Medium
> 25% change	Large

Continuing with the example from above, the CMFs for target crashes are 0.912 for installing centerline rumble strips and 0.844 for installing shoulder rumble strips. The value of 0.912 is defined as small since it represents a change less than 10 percent. The value of 0.844 is defined as medium since it represents a change between 10 and 25 percent.

Step 3: Define the Applicability of Individual CMFs

The third step is to define the applicability of the individual CMFs. Specifically, identify the crash types and severities to which the individual CMFs apply. Refer to the CMF Clearinghouse for more information on the applicability of CMFs (www.cmfclearinghouse.org). Continuing with the example from above, the applicable crash type and severity for both CMFs is all run-off-road, head-on, and sideswipe crashes.

Step 4: Select and Apply an Appropriate Method to Estimate the Combined Effect

The fourth step is to select and apply an appropriate method to estimate the combined effect of the treatments. Follow Figure B1 and use Table B3 or Table B4 to identify the appropriate method based on the considerations in steps 1 – 3. Continuing with the example from above, the following is a summary of the considerations from steps 1 – 3.

- Potential overlap: some (Case B)
- Magnitude of effects: small and medium
- Applicability of CMFs: same crash type and severity

Based on these considerations, the Dominant Common Residuals method is most appropriate. This is determined from Table B3 (same crash type and severity), using Case B (some overlap), and the small-medium category for magnitude of effect.

The following shows the application of the Dominant Common Residuals method based on the CMFs from the example above. Note that the combined CMF is applicable to run-off-road, head-on, and sideswipe crashes on urban and rural, two-lane, undivided roads.

$$\mathrm{CMF_t} = (\mathrm{CMF_1} * \mathrm{CMF_2} * \ldots * \mathrm{CMF_n})^{CMF_1}$$

$$\mathrm{CMF_t} = (0.844 * 0.912)^{0.844}$$

$$\mathrm{CMF_t} = 0.802$$

Estimating the Standard Error of the Combined Safety Effect of Multiple Treatments

The standard error of the CMF is needed for several activities, such as assessing the quality of a CMF and combining multiple CMF estimates for the same treatment. Given that the use of individual CMFs to estimate the combined effect of multiple treatments occurs after the quality rating process and after the combination of individual CMFs for the same treatment, there is limited value or need for the standard error of the combined effect of multiple treatments.

The standard error can be used to estimate the confidence interval of the combined CMF. Practitioners may use the confidence interval to determine a conservative estimate of whether a project is justified (BCR > 1.0), rather than using the mean CMF value. There are two methods available for estimating the standard error of the combined effect for this purpose.

1. The first is the simplest case, and applies to scenarios where the Dominant Effect method is most appropriate to estimate the combined safety effect. Since the Dominant Effect method only applies the lowest CMF (for the most effective treatment), the standard error of the combined effect is the standard error associated with the CMF for the most effective treatment.
2. The second method uses the equation below. The method is based on the theory of multiplying independent random variables (i.e., the Multiplicative method). While this method only applies to the combined effect from the Multiplicative method, assuming independent treatments, it could be used for any of the methods that produce a CMF that represents the combined effect (e.g., Dominant Common Residuals). The method does not recognize the potential overlap among treatment effects, but does provide a reasonable upper bound on the standard error. If the treatment effects overlap, then the method will produce a conservatively high estimate of the standard error.

$$\text{Variance}(CMF_t) = [(CMF_1^2 + \text{Var}(CMF_1)) * (CMF_2^2 + \text{Var}(CMF_2))] - (CMF_t)^2$$

Some of the recommended methods do not produce a combined CMF. Instead, they produce an estimate of the combined effect based on the separate application of individual CMFs. In these cases, the user may apply the standard errors associated with the individual CMFs to estimate the potential range in results for individual crash types and severities.

Extension of Method to Estimate the Combined Safety Effect of Three or More Treatments

The guidance described in this document applies to scenarios where an analyst is interested in combining individual CMFs to estimate the combined effect of two treatments. This was the specific scenario investigated under this research project. It is anticipated that analysts may encounter scenarios where three or more treatments are considered for implementation at the same location. This section describes an option to extend the recommended methods for two treatments to estimate the combined effect of three or more treatments. Analysts should recognize, however, that combining more than two individual CMFs increases the potential for overlapping treatment effects, and this research did not test the accuracy of combining more than two CMFs.

To estimate the effect of three or more treatments, the analyst may follow the general four-step process outlined in Figure B1 and detailed in the above section titled, *Recommended Method to Estimate the Combined Safety Effect of Multiple Two Treatments*. The difference is that CMFs are combined in a pairwise process. Specifically, the analyst would first combine the two individual CMFs associated with the two most effective treatments. The result is a single estimate of the combined effect of the two most effective treatments. The analyst would then combine this estimate with the CMF for the next most effective treatment, again producing a single combined effect. The process continues until there is a single combined effect for all contemplated treatments.

B.3. Example Applications of Procedure

This section provides additional examples to illustrate how to navigate the decision process and then how to apply an appropriate method to estimate the combined effect of two treatments.

Example 1: Complete Overlap among Treatment Effects and Same Applicability

An analyst is considering two treatments, lane widening and shoulder widening, to address safety concerns related to run-off-road crashes on curves along a rural, two-lane, undivided road. Table B8 presents the CMFs and applicability of the CMFs for the individual treatments.

Table B8. CMFs for Lane Widening Only and Shoulder Widening Only on Curves

Treatment	CMF	Applicable Crash Type	Applicable Crash Severity	Applicable Roadway Characteristics	Source
Widen lane width from 11 to 12 feet on curves	0.951	Run-off-road crashes	All	Rural, two-lane, undivided curves	NCHRP 17-63
Widening shoulder width from 3 to 8 feet on curves	0.630	Run-off-road crashes	All	Rural, two-lane, undivided curves	NCHRP 17-63

At this point, the analyst has identified two treatments for potential application, and CMFs are available for the individual treatments in question. Given this information, the analyst can proceed to estimate the combined effect of the treatments.

Step 1: Determine Potential Overlap of Individual Treatment Effects

The first step is to determine the potential overlap of the individual treatment effects, and select the category from Table B6 that best matches the scenario at hand. Lane widening targets head-on, sideswipe opposite direction, and run-off-road crashes. Shoulder widening targets head-on, sideswipe opposite direction, and run-off-road crashes. This suggests that there is complete overlap among the treatments, which corresponds to Case C from Table B6. Specifically, this case represents two non-independent effects where the second treatment targets some or all of the same crash types/severities as the first.

Step 2: Determine Magnitude of Individual Treatment Effects

The second step is to determine the magnitude of the individual treatment effects based on the levels defined in Table B7. The CMFs for run-off-road crashes are 0.951 for lane widening and 0.630 for shoulder widening. The value of 0.951 is defined as small since it represents a change less than 10 percent. The value of 0.630 is defined as large since it represents a change greater 25 percent.

Step 3: Define the Applicability of Individual CMFs

The third step is to define the applicability of the individual CMFs. In this example, the applicable crash type and severity for both CMFs is all run-off-road crashes.

Step 4: Select and Apply an Appropriate Method to Estimate the Combined Effect

The fourth step is to select and apply an appropriate method to estimate the combined effect of the treatments. The following is a summary of the considerations from steps 1 – 3 for this example.

- Potential overlap: complete (Case C)
- Magnitude of effects: small and large
- Applicability of CMFs: same crash type and severity

Based on these considerations, the Dominant Effect method is most appropriate. This is determined from Table B3 (same crash type and severity), using Case C (complete overlap). Note that in this case the magnitude of effect is not applicable.

The following shows the application of the Dominant Effect method based on the CMFs from the example above. Note that the combined CMF is applicable to run-off-road crashes on rural, two-lane, undivided curve sections.

$$\mathrm{CMF_t} = \mathrm{CMF_1}$$

$$\mathrm{CMF_t} = 0.630$$

Example 2: Enhancing Treatment Effects and Same Applicability

An analyst is considering two treatments, installing edgeline pavement markings and shoulder rumble strips, to address safety concerns related to run-off-road crashes on rural, two-lane, undivided roads. From the CMF Clearinghouse, Table B9 presents the CMFs and applicability of the CMFs for the individual treatments.

Table B9. CMFs for Installing Edgeline Pavement Markings and Shoulder Rumble Strips

Treatment	**CMF**	**Applicable Crash Type**	**Applicable Crash Severity**	**Applicable Roadway Characteristics**	**CMF ID**
Install 4-6” edgeline pavement markings	0.97	All	Serious Injury, Minor Injury	Rural, two-lane roads	83
Install shoulder rumble strips	0.92	All	Fatal, Serious Injury, Minor Injury	Rural, two-lane roads	3430

At this point, the analyst has identified two treatments for potential application, and CMFs are available for the individual treatments in question. Given this information, the analyst can proceed to estimate the combined effect of the treatments.

Step 1: Determine Potential Overlap of Individual Treatment Effects

The first step is to determine the potential overlap of the individual treatment effects, and select the category from Table B6 that best matches the scenario at hand. Edgeline pavement markings target run-off-road right crashes, but may affect other crash types such as head-on, sideswipe opposite direction, and run-off-road left. Shoulder rumble strips target run-off-road right crashes, but may affect other crash types such as head-on, sideswipe opposite direction, and run-off-road left. The vertical edge of the rumble strip may enhance the visibility of the edgeline pavement marking if the edgeline is placed within the shoulder rumble strip. Specifically, this case represents a scenario where the combined effect of two treatments is greater than the sum of their individual effects because one treatment is expected to enhance the effectiveness of the other treatment. The potential for enhanced effects corresponds to Case D from Table B6.

Step 2: Determine Magnitude of Individual Treatment Effects

The second step is to determine the magnitude of the individual treatment effects based on the levels defined in Table B7. The CMFs are 0.97 for installing edgeline pavement markings and 0.92 for installing shoulder rumble strips. Both values are defined as small since they represent changes less than 10 percent.

Step 3: Define the Applicability of Individual CMFs

The third step is to define the applicability of the individual CMFs. In this example, the applicable crash type is all crashes for both CMFs. The applicable crash severity for installing pavement markings is serious and minor injury. The applicable crash severity for installing shoulder rumble strips is fatal, serious, and minor injury. For the purpose of this example, the analyst may assume that serious injury crashes include fatal crashes for the first treatment.

Step 4: Select and Apply an Appropriate Method to Estimate the Combined Effect

The fourth step is to select and apply an appropriate method to estimate the combined effect of the treatments. The following is a summary of the considerations from steps 1 – 3 for this example.

- Potential overlap: enhancing effects (Case D)
- Magnitude of effects: small and small
- Applicability of CMFs: same crash type and severity

Based on these considerations, the Additive Effects method is most appropriate with a maximum reduction of 100 percent (i.e., CMF = 0). This is determined from Table B3 (same crash type and severity), using Case D (enhancing effects). Note that in this case the magnitude of effect is not applicable.

The following shows the application of the Additive Effects method based on the CMFs from the example above. Note the combined CMF is applicable to all fatal, serious, and minor injury crashes on rural, two-lane, undivided roads.

$$\mathrm{CMF_t} = 1 - [(1 - \mathrm{CMF_1}) + (1 - \mathrm{CMF_2}) + \cdots + (1 - \mathrm{CMF_n})]$$

$$\mathrm{CMF_t} = 1 - [(1 - 0.92) + (1 - 0.97)]$$

$$\mathrm{CMF_t} = 0.89$$

Note there are CMFs in the CMF Clearinghouse for installing edgeline rumble strips, which may represent the combined effect of installing pavement markings and shoulder rumble strips simultaneously. The CMFs that apply to fatal and injury run-off-road crashes on rural, two-lane, undivided roads range from 0.53 to 0.86. This suggests that there is an enhancing effect of the combined treatment. While the Additive Effects method gives full credit to the individual treatment effects, it does not inflate the combined effect to reflect the potential enhancement.

Example 3: Zero Overlap among Treatment Effects and Different Applicability

This example involves a minor road stop-controlled intersection located near a horizontal curve. An analyst is considering two treatments. The first treatment is installing high friction surface treatment on the curve to address single vehicle run-off-road crashes. The second treatment is improving sight distance on the stop-controlled approach to address multi-vehicle crashes between vehicles on the major and minor road. Table B10 presents the CMFs and applicability of the CMFs for the individual treatments.

Table B10. CMFs for Installing High Friction Surface Treatment Only and Increasing Intersection Sight Distance Only

Treatment	CMF	Applicable Crash Type	Applicable Crash Severity	Applicable Roadway Characteristics	Source
Install high friction surface treatment on curves	0.70	Single vehicle crashes	All	All	CMF Clearinghouse (CMF ID 198)
Increase intersection sight distance to 1,320+ feet (from 500 - 750 feet)	0.456	Multi-vehicle crashes from major and minor road	All	3- and 4-legged intersections with minor-road stop control	NCHRP 17-63

At this point, the analyst has identified two treatments for potential application, and CMFs are available for the individual treatments in question. Given this information, the analyst can proceed to estimate the combined effect of the treatments.

Step 1: Determine Potential Overlap of Individual Treatment Effects

The first step is to determine the potential overlap of the individual treatment effects, and select the category from Table B6 that best matches the scenario at hand. High friction surface treatments on curves target single vehicle, run-off-road crashes. Improving intersection sight distance on a minor road approach targets multi-vehicle crashes between vehicles on the major and minor road. This suggests that there may be no overlap among the treatment effects, corresponding to Case A from Table B6. Specifically, this case represents two independent effects where the complete benefit of both treatments is realized.

Step 2: Determine Magnitude of Individual Treatment Effects

The second step is to determine the magnitude of the individual treatment effects based on the levels defined in Table B7. The CMFs are 0.70 for installing high friction surface treatment and 0.456 for improving intersection sight distance. Both values are defined as large since they represent changes greater than 25 percent.

Step 3: Define the Applicability of Individual CMFs

The third step is to define the applicability of the individual CMFs. In this example, the applicable crash type and severity for installing high friction surface treatment is all single vehicle crashes. The applicable crash type and severity for improving intersection sight distance is all multi-vehicle crashes between vehicles on the major and minor road.

Step 4: Select and Apply an Appropriate Method to Estimate the Combined Effect

The fourth step is to select and apply an appropriate method to estimate the combined effect of the treatments. The following is a summary of the considerations from steps 1 – 3 for this example.

- Potential overlap: none (Case A)
- Magnitude of effects: large and large
- Applicability of CMFs: different crash type and severity

Based on these considerations, the Additive Effects method is most appropriate with a maximum reduction of 100 percent (i.e., CMF = 0). This is determined from Table B4 (different crash type and severity), using Case A (zero overlap). Note that in this case the magnitude of effect is not applicable.

The following shows the application of the Additive Effects method based on the CMFs from the example above. Note that this method does not produce a combined CMF. Instead, it produces an estimate of the combined effect. For this example, assume the estimated single vehicle crashes without treatment is 3.4 crashes per year, and the estimated multi-vehicle crashes between vehicles on the major and minor road is 5.2 crashes per year.

1. Apply the CMF for the first treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest.

   Estimated crashes with treatment = CMF * Estimated crashes without treatment

   Estimated single vehicle crashes with high friction surface treatment = 0.70 * 3.4

   Estimated single vehicle crashes with high friction surface treatment = 2.38

   Estimated reduction in single vehicle crashes = 3.4 – 2.38 = 1.02

2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest.

   Estimated multi-vehicle crashes with improved sight distance = 0.456 * 5.2

   Estimated multi-vehicle crashes with improved sight distance = 2.37

   Estimated reduction in multi-vehicle crashes = 5.2 – 2.37 = 2.83

3. Sum the estimated change in crashes to calculate the net effect.

   Sum of estimated reductions = 1.02 + 2.83 = 3.85

4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.

   Sum of estimated reductions (3.85) < Estimated crashes without treatment (8.6)

Example 4: Some Overlap among Treatment Effects and Different Applicability

An analyst is considering two treatments on a rural, four-lane, divided highway with a traversable median. The first treatment is installing high-tension cable median barrier to address cross-median crashes. The second treatment is installing shoulder rumble strips to address run-off-road and cross-median crashes. From the CMF Clearinghouse, Table B11 presents the CMFs and general applicability for the individual treatments.

Table B11. CMFs for Installing High-Tension Cable Median Barrier and Shoulder Rumble Strips

Treatment	CMF	Applicable Crash Type	Applicable Crash Severity	Applicable Roadway Characteristics	CMF ID
Install high-tension cable median barrier	0.04	Cross-median	All	Rural, multilane interstates with traversable medians	1967
Install shoulder rumble strips	0.87	Cross-median and run-off-road	All	Rural, four-lane freeways with traversable medians	6965

At this point, the analyst has identified two treatments for potential application, and CMFs are available for the individual treatments in question. Given this information, the analyst can proceed to estimate the combined effect of the treatments.

Step 1: Determine Potential Overlap of Individual Treatment Effects

The first step is to determine the potential overlap of the individual treatment effects, and select the category from Table B6 that best matches the scenario at hand. High-tension cable median barrier targets cross-median crashes, including head-on and opposite direction sideswipe. Shoulder rumble strips target run-off-road crashes as well as the head-on and opposite direction sideswipe crashes related to vehicles crossing the median. This suggests that there is some overlap among the treatment effects, corresponding to Case B from Table B6. Specifically, this case represents two treatments that both provide some level of benefit in reducing cross-median crashes, and the second treatment has an additional effect on run-off-road crashes.

Step 2: Determine Magnitude of Individual Treatment Effects

The second step is to determine the magnitude of the individual treatment effects based on the levels defined in Table B7. The CMFs are 0.04 for installing high-tension cable median barrier and 0.87 for installing shoulder rumble strips. The CMF of 0.04 is defined as large since it represents a change greater than 25 percent. The CMF of 0.87 is defined as medium since it represents a change between 10 and 25 percent.

Step 3: Define the Applicability of Individual CMFs

The third step is to define the applicability of the individual CMFs. In this example, the applicable crash type and severity for installing high-tension cable median barrier is all cross-median crashes. The applicable crash type and severity for installing shoulder rumble strips is all run-off-road and cross-median crashes.

Step 4: Select and Apply an Appropriate Method to Estimate the Combined Effect

The fourth step is to select and apply an appropriate method to estimate the combined effect of the treatments. The following is a summary of the considerations from steps 1 – 3 for this example.

- Potential overlap: some (Case B)
- Magnitude of effects: large and medium
- Applicability of CMFs: different crash type and severity

Based on these considerations, the Dominant Effect for Overlapping Crash Types method is most appropriate. This is determined from Table B4 (different crash type and severity), using Case B (some overlap). Note that in this case the magnitude of effect is not applicable.

The following shows the application of the Dominant Effect for Overlapping Crash Types method based on the CMFs from the example above. Note that this method does not produce a combined CMF. Instead, it produces an estimate of the combined effect. For this example, assume the estimated crashes without treatment is 8.9 crashes per year, which includes 2.3 cross-median head-on crashes, 1.3 cross-median sideswipe opposite direction crashes, and 5.3 run-off-road crashes.

1. Apply the CMF for the most effective treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest.

   Estimated crashes with treatment = CMF * Estimated crashes without treatment

   Estimated cross-median crashes with high-tension cable barrier = 0.04 * 3.6

   Estimated cross-median crashes with high-tension cable barrier = 0.14

   Estimated reduction in cross-median crashes = 3.6 – 0.14 = 3.46

2. Apply the CMF for the second treatment to the estimated crashes without treatment for the applicable crash type/severity at the location of interest, excluding crashes associated with the most effective treatment. Note that the CMF for the first treatment was applied to all cross-median crashes. As such, cross-median crashes are excluded from further analysis, and the second treatment only applies to run-off-road crashes.

   Estimated run-off-road crashes with shoulder rumble strips = 0.87 * 5.3

   Estimated run-off-road crashes with shoulder rumble strips = 4.61

   Estimated reduction in run-off-road crashes = 5.3 – 4.61 = 0.69

3. Sum the estimated change in crashes to calculate the net effect.

   Sum of estimated reductions = 3.46 + 0.69 = 4.15

4. Check that the estimated change does not exceed the potential bounds of the combined treatments. If so, the estimated change is equal to the respective bound.

   Sum of estimated reductions (4.15) < Estimated crashes without treatment (8.9)

B.4. Supporting Research

Introduction

This section on supporting research provides details related to the CMF development effort to develop the procedure for estimating the combined safety effect of two treatments at the same location. The team for Project 17-63 developed CMFs for the following three combination treatments, including CMFs for both the individual and combined treatment effects.

1. Combination of centerline and shoulder rumble strip installation on urban and rural, two-lane, undivided roads,
2. Combination of lane and shoulder widening on rural, two-lane, undivided roads, and
3. Combination of intersection skew angle and sight distance improvements at three- and four-legged intersections with minor-road stop control.

The remainder of this section provides details related to each of the CMF development efforts, including the methodology and related safety performance functions.

Combination of Centerline and Shoulder Rumble Strip Installation

For this analysis, the team was able to employ a rigorous empirical Bayes before-after method to estimate CMFs for the individual treatment effects (i.e., CLRS only and SRS only) as well as the combined treatment effect (i.e., CLRS+SRS).

The EB method is a proven technique in highway safety that can account for bias due to regression-to-the-mean (RTM), changes in traffic volume, and temporal trends (i.e., general trends over time). The premise of this method is to estimate what would have occurred in the after period without treatment and compare that to what actually occurred in the after period with treatment. Due to changes in safety that may result from changes in RTM, traffic volume, and temporal trends, the count of crashes before a treatment by itself is not a good estimate of π (Hauer, 1997). Instead, π is estimated from an EB procedure (Hauer, 1997) in which a safety performance function (SPF) is used to first predict the number of crashes in each year of the "before" period based on locations with traffic volumes and other characteristics similar to the treatment sites. The sum of these annual SPF estimates (P) is then combined with the count of crashes in the before period at the treatment site (x) to obtain an estimate of the expected number of crashes before the treatment (m). The following equation provides an estimate of m.

Equation B1

$$m = (w)(P) + (1-w)(x)$$

The following equation provides the weight (w).

Equation B2

$$w = 1/(1 + P/\alpha)$$

Where,

m = expected number of crashes before the treatment,
w = weight to estimate EB expected crashes,
P = sum of annual SPF estimates "before" treatment at the treatment sites, and
α = inverse of the dispersion parameter from the SPF. Note the value of α is estimated from the SPF calibration process with the use of a maximum likelihood procedure and a larger value of α indicates less dispersion.

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of the expected number of crashes that would have occurred in the “after” period without the treatment (π).

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

The index of safety effectiveness (θ) represents the CMF and is given by the following equation.

Equation B3

$$\theta = (\lambda_{sum} / \pi_{sum}) \,/\, \{1 + [Var(\pi_{sum}) / \pi_{sum}^2]\}$$

The standard deviation of θ is given by the following equation.

Equation B4

$$Stddev\,(\theta) = [\theta^2 \{[Var\,(\lambda_{sum}) / \lambda_{sum}^2] + [Var\,(\pi_{sum}) / \pi_{sum}^2]\} \,/\, [1 + Var\,(\pi_{sum}) / \pi_{sum}^2]^2]^{0.5}$$

Where,

θ = index of safety effectiveness (crash modification factor),
π = expected number of crashes in the “after” period without treatment,
λ = number of reported crashes in the after period, and
Stddev = standard deviation.

The selection of an appropriate reference group is critical to the EB method. A suitable reference group is a group of sites that are similar to the treatment sites in terms of geometric and traffic characteristics except they did not receive the treatment. If a reference group is located in the general vicinity of the treatment sites, it can be used to account for temporal trends (e.g. weather) that influence crashes. In this study, the reference sites were selected from the same general areas as the treatment sites, and propensity score matching was employed to identify a suitable reference group for each treatment category.

Fundamental to the EB approach is the use of SPFs. An SPF is a mathematical model that predicts the mean crash frequency for locations with similar characteristics. Generalized linear modeling (GLM) techniques were applied to calibrate SPFs for each target crash type (total, fatal and injury, run-off-road, and target crashes). A log-linear relationship was specified using a negative binomial error structure, which is consistent with the state of research in developing SPFs. Model coefficients were estimated using the software package Stata. The remainder of this section presents the SPFs developed for each focus crash type. The following is the general form of the SPFs.

Equation B5

$$SPF = length * e^{constant + \beta 1 * \log(AADT) + \beta 2 * X2 + \ldots + \beta n * Xn}$$

Where,

length = segment length (miles),
Constant = constant estimated during modeling process,
Log(AADT) = natural log of traffic volume,
$\beta_1 - \beta_n$ = Coefficients estimated during modeling process, and
$X_2 - X_n$ = variables included in given SPF.

Table B12. Total Crash SPF for Centerline Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	1.0165	0.0198	51.34	0.0000	0.9777	1.0553
Area Type (1=urban; 0 otherwise)	0.0622	0.0464	1.34	0.1800	-0.0287	0.1532
Terrain (1=rolling; 0 otherwise)	-0.2048	0.0357	-5.73	0.0000	-0.2749	-0.1348
Speed Limit (1=50+mph; 0 otherwise)	-0.4061	0.0450	-9.02	0.0000	-0.4943	-0.3179
Lane Width (1=11ft; 0=12ft or 13ft)	0.1954	0.0709	2.75	0.0060	0.0564	0.3344
Shoulder Width (continuous)	-0.0429	0.0081	-5.27	0.0000	-0.0589	-0.0270
Lane Width * Shoulder Width	-0.0315	0.0132	-2.38	0.0170	-0.0573	-0.0056
Indicator for Year = 2003	0.0032	0.0742	0.04	0.9660	-0.1422	0.1485
Indicator for Year = 2004	-0.0682	0.0746	-0.91	0.3610	-0.2144	0.0781
Indicator for Year = 2005	-0.0355	0.0740	-0.48	0.6310	-0.1806	0.1096
Indicator for Year = 2006	-0.0307	0.0743	-0.41	0.6790	-0.1764	0.1149
Indicator for Year = 2007	-0.0094	0.0738	-0.13	0.8990	-0.1540	0.1352
Indicator for Year = 2008	0.0472	0.0737	0.64	0.5220	-0.0973	0.1916
Indicator for Year = 2009	-0.0461	0.0745	-0.62	0.5360	-0.1920	0.0999
Indicator for Year = 2010	-0.0889	0.0750	-1.19	0.2360	-0.2358	0.0580
Indicator for Year = 2011	-0.1210	0.0774	-1.56	0.1180	-0.2727	0.0306
Indicator for Year = 2012	-0.2515	0.0794	-3.17	0.0020	-0.4071	-0.0960
Constant	-7.0646	0.1880	-37.58	0.0000	-7.4330	-6.6962
alpha (α)	0.4219	0.0247			0.3762	0.4731

Table B13. Fatal and Injury Crash SPF for Centerline Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	1.0190	0.0262	38.88	0.0000	0.9676	1.0703
Area Type (1=urban; 0 otherwise)	0.0676	0.0598	1.13	0.2580	-0.0497	0.1849
Terrain (1=rolling; 0 otherwise)	-0.2010	0.0464	-4.33	0.0000	-0.2919	-0.1101
Speed Limit (1=50+mph; 0 otherwise)	-0.4142	0.0587	-7.06	0.0000	-0.5293	-0.2992
Lane Width (1=11ft; 0=12ft or 13ft)	0.3718	0.0922	4.03	0.0000	0.1910	0.5525
Shoulder Width (continuous)	-0.0335	0.0109	-3.09	0.0020	-0.0548	-0.0122
Lane Width * Shoulder Width	-0.0672	0.0172	-3.91	0.0000	-0.1009	-0.0336
Indicator for Year = 2003	-0.0109	0.0935	-0.12	0.9070	-0.1941	0.1724
Indicator for Year = 2004	-0.1292	0.0951	-1.36	0.1740	-0.3156	0.0571
Indicator for Year = 2005	-0.0520	0.0938	-0.55	0.5800	-0.2359	0.1319
Indicator for Year = 2006	-0.0091	0.0940	-0.10	0.9230	-0.1935	0.1752
Indicator for Year = 2007	0.0080	0.0928	0.09	0.9310	-0.1739	0.1898
Indicator for Year = 2008	-0.0537	0.0944	-0.57	0.5700	-0.2388	0.1314
Indicator for Year = 2009	-0.0683	0.0947	-0.72	0.4710	-0.2538	0.1172
Indicator for Year = 2010	-0.2321	0.0976	-2.38	0.0170	-0.4234	-0.0407
Indicator for Year = 2011	-0.3184	0.1024	-3.11	0.0020	-0.5190	-0.1177
Indicator for Year = 2012	-0.4898	0.1064	-4.60	0.0000	-0.6984	-0.2812
Constant	-7.9930	0.2476	-32.28	0.0000	-8.4784	-7.5076
alpha (α)	0.3888	0.0382			0.3208	0.4713

Table B14. Run-Off-Road Crash SPF for Centerline Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.5426	0.0242	22.43	0.0000	0.4952	0.5900
Terrain (1=mountainous; 0 otherwise)	0.4070	0.1134	3.59	0.0000	0.1847	0.6292
Speed Limit (1=50+mph; 0 otherwise)	-0.1116	0.0674	-1.66	0.0980	-0.2436	0.0205
Lane Width (1=11ft; 0=12ft or 13ft)	0.7063	0.0951	7.42	0.0000	0.5198	0.8928
Shoulder Width (continuous)	-0.0291	0.0125	-2.32	0.0200	-0.0537	-0.0045
Lane Width * Shoulder Width	-0.0986	0.0183	-5.38	0.0000	-0.1345	-0.0627
Indicator for Year = 2003	0.0868	0.1018	0.85	0.3940	-0.1128	0.2863
Indicator for Year = 2004	0.0477	0.1028	0.46	0.6430	-0.1539	0.2493
Indicator for Year = 2005	0.2078	0.1001	2.08	0.0380	0.0115	0.4040
Indicator for Year = 2006	0.1314	0.1014	1.30	0.1950	-0.0673	0.3301
Indicator for Year = 2007	0.1382	0.1012	1.37	0.1720	-0.0602	0.3366
Indicator for Year = 2008	0.1580	0.1011	1.56	0.1180	-0.0400	0.3561
Indicator for Year = 2009	0.0398	0.1031	0.39	0.6990	-0.1623	0.2419
Indicator for Year = 2010	0.0945	0.1026	0.92	0.3570	-0.1065	0.2956
Indicator for Year = 2011	0.0219	0.1066	0.21	0.8370	-0.1870	0.2308
Indicator for Year = 2012	-0.0673	0.1096	-0.61	0.5390	-0.2822	0.1475
Constant	-4.9246	0.2279	-21.61	0.0000	-5.3713	-4.4779
alpha (α)	0.4160	0.0424			0.3407	0.5081

Table B15. Target Crash SPF for Centerline Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.5708	0.0257	22.23	0.0000	0.5204	0.6211
Area Type (1=urban; 0 otherwise)	0.0980	0.0692	1.42	0.1570	-0.0376	0.2335
Terrain (1=mountainous; 0 otherwise)	0.3985	0.1122	3.55	0.0000	0.1786	0.6183
Speed Limit (1=50+mph; 0 otherwise)	-0.0716	0.0667	-1.07	0.2830	-0.2023	0.0591
Lane Width (1=11ft; 0=12ft or 13ft)	0.6860	0.0924	7.42	0.0000	0.5049	0.8672
Shoulder Width (continuous)	-0.0332	0.0122	-2.73	0.0060	-0.0571	-0.0094
Lane Width * Shoulder Width	-0.0957	0.0177	-5.41	0.0000	-0.1304	-0.0611
Indicator for Year = 2003	0.0745	0.0982	0.76	0.4480	-0.1179	0.2669
Indicator for Year = 2004	0.0067	0.0995	0.07	0.9470	-0.1884	0.2017
Indicator for Year = 2005	0.1645	0.0970	1.70	0.0900	-0.0256	0.3546
Indicator for Year = 2006	0.0783	0.0983	0.80	0.4260	-0.1144	0.2711
Indicator for Year = 2007	0.1310	0.0974	1.35	0.1790	-0.0599	0.3219
Indicator for Year = 2008	0.1393	0.0975	1.43	0.1530	-0.0518	0.3304
Indicator for Year = 2009	0.0332	0.0992	0.33	0.7380	-0.1612	0.2275
Indicator for Year = 2010	0.0492	0.0994	0.49	0.6210	-0.1457	0.2440
Indicator for Year = 2011	0.0122	0.1027	0.12	0.9050	-0.1891	0.2135
Indicator for Year = 2012	-0.1134	0.1061	-1.07	0.2850	-0.3214	0.0946
Constant	-5.0672	0.2317	-21.87	0.0000	-5.5212	-4.6131
alpha (α)	0.4139	0.0401			0.3422	0.5005

Table B16. Total Crash SPF for Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.1148	0.1588	0.72	0.4700	-0.1965	0.4261
Area Type (1=urban; 0 otherwise)	1.2014	0.2675	4.49	0.0000	0.6771	1.7256
Speed Limit (1=50+mph; 0 otherwise)	-0.6647	0.3510	-1.89	0.0580	-1.3527	0.0232
Lane Width (1=11ft; 0=12ft or 13ft)	0.8643	0.4466	1.94	0.0530	-0.0110	1.7396
Shoulder Width (continuous)	0.0839	0.0489	1.72	0.0860	-0.0119	0.1798
Lane Width * Shoulder Width	-0.1709	0.0773	-2.21	0.0270	-0.3223	-0.0195
Indicator for Year = 2006	0.0553	0.2174	0.25	0.7990	-0.3708	0.4814
Indicator for Year = 2007	-0.2013	0.2301	-0.87	0.3820	-0.6522	0.2497
Indicator for Year = 2008	0.1182	0.2143	0.55	0.5810	-0.3018	0.5383
Indicator for Year = 2009	0.0696	0.2175	0.32	0.7490	-0.3566	0.4958
Indicator for Year = 2010	-0.0270	0.2202	-0.12	0.9020	-0.4586	0.4046
Indicator for Year = 2011	0.1540	0.2132	0.72	0.4700	-0.2638	0.5718
Indicator for Year = 2012	-0.1870	0.2286	-0.82	0.4130	-0.6351	0.2611
Constant	-0.1770	1.3863	-0.13	0.8980	-2.8940	2.5401
alpha (α)	0.0783	0.0589			0.0179	0.3423

Table B17. Fatal and Injury Crash SPF for Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.2283	0.2534	0.90	0.3680	-0.2684	0.7250
Area Type (1=urban; 0 otherwise)	1.4351	0.3951	3.63	0.0000	0.6606	2.2096
Speed Limit (1=50+mph; 0 otherwise)	-0.2038	0.5649	-0.36	0.7180	-1.3109	0.9034
Lane Width (1=11ft; 0=12ft or 13ft)	1.0508	0.5916	1.78	0.0760	-0.1087	2.2102
Shoulder Width (continuous)	-0.0267	0.0785	-0.34	0.7340	-0.1806	0.1272
Lane Width * Shoulder Width	-0.1631	0.1016	-1.61	0.1080	-0.3622	0.0359
Indicator for Year = 2006	-0.0419	0.2970	-0.14	0.8880	-0.6240	0.5402
Indicator for Year = 2007	-0.2420	0.3080	-0.79	0.4320	-0.8456	0.3616
Indicator for Year = 2008	0.1388	0.2827	0.49	0.6240	-0.4153	0.6929
Indicator for Year = 2009	0.1333	0.2863	0.47	0.6410	-0.4279	0.6946
Indicator for Year = 2010	-0.2935	0.3125	-0.94	0.3480	-0.9059	0.3190
Indicator for Year = 2011	-0.0533	0.2967	-0.18	0.8570	-0.6349	0.5282
Indicator for Year = 2012	-0.4466	0.3293	-1.36	0.1750	-1.0921	0.1989
Constant	-1.7774	2.2068	-0.81	0.4210	-6.1028	2.5479
alpha (α)	0.0376	0.1198			0.0001	19.4069

Table B18. Run-Off-Road Crash SPF for Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.2751	0.1162	2.37	0.0180	0.0473	0.5029
Area Type (1=urban; 0 otherwise)	-0.1448	0.2481	-0.58	0.5590	-0.6311	0.3414
Terrain1 (1=mountainous; 0=flat)	1.1534	0.5510	2.09	0.0360	0.0736	2.2333
Terrain2 (1=rolling; 0=flat)	0.5699	0.5437	1.05	0.2950	-0.4958	1.6357
Speed Limit (1=50+mph; 0 otherwise)	-0.3346	0.2709	-1.24	0.2170	-0.8655	0.1964
Lane Width (1=11ft; 0=12ft or 13ft)	0.8376	0.4315	1.94	0.0520	-0.0081	1.6833
Shoulder Width (continuous)	-0.0472	0.0328	-1.44	0.1500	-0.1115	0.0171
Lane Width * Shoulder Width	-0.0918	0.0760	-1.21	0.2270	-0.2408	0.0572
Indicator for Year = 2007	0.2270	0.4209	0.54	0.5900	-0.5980	1.0519
Indicator for Year = 2008	0.0846	0.3922	0.22	0.8290	-0.6842	0.8533
Indicator for Year = 2009	0.2288	0.3896	0.59	0.5570	-0.5349	0.9924
Indicator for Year = 2010	0.1111	0.3907	0.28	0.7760	-0.6546	0.8767
Indicator for Year = 2011	0.2360	0.3879	0.61	0.5430	-0.5243	0.9963
Indicator for Year = 2012	-0.0219	0.3943	-0.06	0.9560	-0.7947	0.7510
Constant	-2.6433	1.2837	-2.06	0.0390	-5.1594	-0.1273
alpha (α)	0.1964	0.0961			0.0753	0.5124

Table B19. Target Crash SPF for Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.3393	0.1137	2.99	0.0030	0.1165	0.5620
Area Type (1=urban; 0 otherwise)	-0.1857	0.2410	-0.77	0.4410	-0.6581	0.2867
Terrain1 (1=mountainous; 0=flat)	1.2699	0.5501	2.31	0.0210	0.1917	2.3480
Terrain2 (1=rolling; 0=flat)	0.6700	0.5433	1.23	0.2180	-0.3949	1.7348
Speed Limit (1=50+mph; 0 otherwise)	-0.2089	0.2697	-0.77	0.4390	-0.7374	0.3196
Lane Width (1=11ft; 0=12ft or 13ft)	0.8020	0.4233	1.89	0.0580	-0.0276	1.6315
Shoulder Width (continuous)	-0.0514	0.0319	-1.61	0.1070	-0.1139	0.0111
Lane Width * Shoulder Width	-0.0811	0.0746	-1.09	0.2770	-0.2272	0.0650
Indicator for Year = 2007	0.2945	0.4040	0.73	0.4660	-0.4975	1.0864
Indicator for Year = 2008	0.0959	0.3778	0.25	0.8000	-0.6446	0.8364
Indicator for Year = 2009	0.1851	0.3763	0.49	0.6230	-0.5523	0.9226
Indicator for Year = 2010	0.1389	0.3757	0.37	0.7120	-0.5975	0.8752
Indicator for Year = 2011	0.2571	0.3731	0.69	0.4910	-0.4741	0.9883
Indicator for Year = 2012	-0.0552	0.3805	-0.15	0.8850	-0.8010	0.6906
Constant	-3.3114	1.2576	-2.63	0.0080	-5.7763	-0.8465
alpha (α)	0.2073	0.0923			0.0866	0.4962

Table B20. Total Crash SPF for Combination of Centerline and Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	1.0939	0.0493	22.21	0.0000	0.9974	1.1905
Area Type (1=urban; 0 otherwise)	-0.1445	0.1246	-1.16	0.2460	-0.3887	0.0996
Terrain (1=mountainous; 0 otherwise)	-0.3433	0.1924	-1.78	0.0740	-0.7204	0.0338
Speed Limit (1=50+mph; 0 otherwise)	-0.1947	0.1283	-1.52	0.1290	-0.4461	0.0567
Lane Width (1=11ft; 0=12ft or 13ft)	0.7394	0.1818	4.07	0.0000	0.3831	1.0956
Lane Width * Shoulder Width	-0.1034	0.0294	-3.51	0.0000	-0.1611	-0.0457
Indicator for Year = 2003	0.1981	0.1686	1.18	0.2400	-0.1323	0.5285
Indicator for Year = 2004	0.0140	0.1720	0.08	0.9350	-0.3231	0.3512
Indicator for Year = 2005	-0.0379	0.1736	-0.22	0.8270	-0.3782	0.3023
Indicator for Year = 2006	0.0837	0.1705	0.49	0.6230	-0.2505	0.4180
Indicator for Year = 2007	-0.0576	0.1730	-0.33	0.7390	-0.3966	0.2814
Indicator for Year = 2008	0.0702	0.1725	0.41	0.6840	-0.2680	0.4083
Indicator for Year = 2009	0.0290	0.1724	0.17	0.8660	-0.3088	0.3669
Indicator for Year = 2010	-0.1805	0.1756	-1.03	0.3040	-0.5247	0.1637
Indicator for Year = 2011	-0.1073	0.1803	-0.60	0.5520	-0.4608	0.2461
Indicator for Year = 2012	-0.0244	0.1806	-0.13	0.8930	-0.3783	0.3296
Constant	-8.3076	0.4773	-17.40	0.0000	-9.2431	-7.3721
alpha (α)	0.4675	0.0538			0.3731	0.5858

Table B21. Fatal and Injury Crash SPF for Combination of Centerline and Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	1.2163	0.0666	18.27	0.0000	1.0858	1.3468
Area Type (1=urban; 0 otherwise)	-0.4785	0.1813	-2.64	0.0080	-0.8338	-0.1232
Terrain (1=mountainous; 0 otherwise)	-0.7454	0.2488	-3.00	0.0030	-1.2332	-0.2577
Speed Limit (1=50+mph; 0 otherwise)	-0.2314	0.1742	-1.33	0.1840	-0.5728	0.1100
Lane Width (1=11ft; 0=12ft or 13ft)	0.4481	0.2422	1.85	0.0640	-0.0266	0.9228
Lane Width * Shoulder Width	-0.0878	0.0396	-2.22	0.0260	-0.1653	-0.0103
Indicator for Year = 2003	-0.0088	0.2189	-0.04	0.9680	-0.4379	0.4203
Indicator for Year = 2004	-0.0355	0.2173	-0.16	0.8700	-0.4615	0.3904
Indicator for Year = 2005	-0.1721	0.2227	-0.77	0.4400	-0.6085	0.2644
Indicator for Year = 2006	-0.1420	0.2220	-0.64	0.5220	-0.5771	0.2930
Indicator for Year = 2007	-0.4480	0.2319	-1.93	0.0530	-0.9026	0.0066
Indicator for Year = 2008	-0.2813	0.2294	-1.23	0.2200	-0.7309	0.1684
Indicator for Year = 2009	-0.1486	0.2215	-0.67	0.5020	-0.5829	0.2856
Indicator for Year = 2010	-0.6672	0.2399	-2.78	0.0050	-1.1375	-0.1969
Indicator for Year = 2011	-0.4677	0.2433	-1.92	0.0550	-0.9446	0.0092
Indicator for Year = 2012	-0.3883	0.2405	-1.61	0.1060	-0.8597	0.0830
Constant	-9.9505	0.6450	-15.43	0.0000	-11.2146	-8.6864
alpha (α)	0.5349	0.0949			0.3777	0.7574

Table B22. Run-Off-Road Crash SPF for Combination of Centerline and Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.4859	0.0593	8.20	0.0000	0.3697	0.6020
Terrain (1=mountainous; 0 otherwise)	0.6483	0.2768	2.34	0.0190	0.1057	1.1908
Speed Limit (1=50+mph; 0 otherwise)	0.3807	0.2616	1.46	0.1460	-0.1321	0.8935
Lane Width (1=11ft; 0=12ft or 13ft)	1.2929	0.3456	3.74	0.0000	0.6155	1.9703
Shoulder Width (continuous)	-0.0461	0.0371	-1.24	0.2140	-0.1187	0.0266
Lane Width * Shoulder Width	-0.2061	0.0530	-3.89	0.0000	-0.3099	-0.1022
Indicator for Year = 2003	0.2212	0.2113	1.05	0.2950	-0.1930	0.6354
Indicator for Year = 2004	-0.3031	0.2359	-1.29	0.1990	-0.7655	0.1592
Indicator for Year = 2005	-0.2575	0.2338	-1.10	0.2710	-0.7157	0.2007
Indicator for Year = 2006	-0.0718	0.2252	-0.32	0.7500	-0.5132	0.3696
Indicator for Year = 2007	0.0300	0.2191	0.14	0.8910	-0.3993	0.4594
Indicator for Year = 2008	-0.1649	0.2288	-0.72	0.4710	-0.6135	0.2836
Indicator for Year = 2009	-0.2012	0.2308	-0.87	0.3830	-0.6537	0.2512
Indicator for Year = 2010	-0.1904	0.2290	-0.83	0.4060	-0.6392	0.2583
Indicator for Year = 2011	-0.1121	0.2334	-0.48	0.6310	-0.5696	0.3455
Indicator for Year = 2012	-0.3132	0.2487	-1.26	0.2080	-0.8006	0.1741
Constant	-4.5388	0.6615	-6.86	0.0000	-5.8353	-3.2423
alpha (α)	0.2203	0.0805			0.1077	0.4507

Table B23. Target Crash SPF for Combination of Centerline and Shoulder Rumble Strips

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT)	0.5345	0.0569	9.39	0.0000	0.4229	0.6460
Terrain (1=mountainous; 0 otherwise)	0.4231	0.2683	1.58	0.1150	-0.1027	0.9489
Speed Limit (1=50+mph; 0 otherwise)	0.4520	0.2541	1.78	0.0750	-0.0460	0.9500
Lane Width (1=11ft; 0=12ft or 13ft)	1.1693	0.3315	3.53	0.0000	0.5195	1.8191
Shoulder Width (continuous)	-0.0513	0.0354	-1.45	0.1470	-0.1207	0.0180
Lane Width * Shoulder Width	-0.1953	0.0510	-3.83	0.0000	-0.2952	-0.0954
Indicator for Year = 2003	0.1786	0.2039	0.88	0.3810	-0.2210	0.5782
Indicator for Year = 2004	-0.3356	0.2271	-1.48	0.1400	-0.7808	0.1096
Indicator for Year = 2005	-0.3176	0.2263	-1.40	0.1610	-0.7612	0.1260
Indicator for Year = 2006	-0.0763	0.2157	-0.35	0.7240	-0.4990	0.3464
Indicator for Year = 2007	0.0013	0.2110	0.01	0.9950	-0.4123	0.4148
Indicator for Year = 2008	-0.1351	0.2180	-0.62	0.5350	-0.5623	0.2921
Indicator for Year = 2009	-0.1214	0.2180	-0.56	0.5780	-0.5487	0.3058
Indicator for Year = 2010	-0.2763	0.2229	-1.24	0.2150	-0.7132	0.1606
Indicator for Year = 2011	-0.0712	0.2221	-0.32	0.7480	-0.5065	0.3641
Indicator for Year = 2012	-0.2937	0.2372	-1.24	0.2160	-0.7587	0.1713
Constant	-4.8442	0.6359	-7.62	0.0000	-6.0905	-3.5978
alpha (α)	0.2210	0.0755			0.1131	0.4315

Combination of Lane and Shoulder Widening

For this analysis, the team employed a rigorous cross-sectional method to estimate CMFs for the individual and combined treatment effects. The two combined treatments of interest for tangent sections are: 1) 12-ft lanes and 4-ft shoulders compared to 11-ft lanes and 3-ft shoulders, and 2) 12-ft lanes and 8-ft shoulders compared to 11-ft lanes and 3-ft shoulders. The two combined treatments of interest for horizontal curve sections are: 1) 12-ft lanes and 4-ft shoulders compared to 11-ft lanes and 2-ft shoulders, and 2) 12-ft lanes and 8-ft shoulders compared to 11-ft lanes and 2-ft shoulders.

A cross-sectional study design is a type of observational study used to analyze a representative sample at a specific point in time. The safety effect is estimated by taking the ratio of the average crash frequency for two groups, one with the feature of interest and the other without the feature of interest. For this method to work, the two groups should be similar in all regards except for the feature of interest. To minimize differences among the groups, propensity score matching was employed, and multivariate regression models were used to estimate the safety effects of one feature while controlling for other characteristics that vary among sites.

Multivariate regression was used to develop a statistical relationship between the dependent variable and a set of predictor variables. In this case, crash frequency was the dependent variable of interest and several predictor variables were considered, including lane width, shoulder width, and other roadway and operational characteristics. Coefficients were estimated during the modeling process for each of the predictor variables. The coefficients represent the expected change in the dependent variable (crash frequency) due to a unit change in the predictor variable, all else being equal.

The current state-of-the-practice for developing crash prediction models is to assume a log-linear relationship between crash frequency and site characteristics. GLM techniques were applied to develop the models, and a log-linear relationship was specified using a negative binomial error structure. The negative binomial error structure also has advantages over the Poisson distribution in that it allows for over-dispersion of the variance that is often present in crash data.

There are several potential sources of bias in the development of crash prediction models. The following is a list of potential sources of bias with an explanation of how they were addressed:

- *Selection of appropriate functional form:* Functional form relates to both the overall form of the model and the form of each independent variable. The current state-of-the-practice was used for the overall form of the model (i.e., log-linear relationship), and exploratory data analysis techniques were used to identify an appropriate form for each predictor.
- *Correlation among independent variables:* Correlation refers to the degree of association among variables. A high degree of correlation among the predictor variables makes it difficult to determine a reliable estimate of the effects of specific predictor variables. The correlation matrix was examined to determine the extent of correlation among independent variables, and used to prioritize variables for inclusion.
- *Over-fitting of prediction models:* Over-fitting is related to the concept of diminishing returns. At some point, it is not worth adding any more independent variables to the model because they do not significantly improve the model fit. Over-fitting also increases the opportunity to introduce inter-correlation between independent variables, and the opportunity for small sample issues when considering indicator variables. Several combinations of predictor variables were considered, and relative goodness-of-fit (GOF) measures were employed to penalize models with greater estimated parameters.

The multivariate models were developed by identifying base models with traffic volume only, exploring the effects of adding other predictor variables to the models, and then selecting the final model. Having developed the base models for each crash type (traffic volume only), additional variables were considered. Once a variable was included in the model, the estimated parameters and associated standard errors were examined to determine the following:

- Is the direction of effect (i.e., expected decrease or increase in crashes) in general agreement with expectations?
- Does the magnitude of the effect seem reasonable?
- Are the parameters of the model estimated with statistical significance?
- Does the estimated over-dispersion parameter improve significantly?

The remainder of this section presents the SPFs developed for each focus crash type (i.e., total, fatal and injury, run-off-road, and target crashes). The following is the general form of the SPFs.

Equation B6

$$SPF = length*e^{constant + \beta1*log(AADT) + \beta2*X2 + \ldots + \beta n*Xn}$$

Where,

length = segment length (miles),
Constant = constant estimated during modeling process,
Log(AADT) = natural log of traffic volume,
$\beta_1 - \beta_n$ = Coefficients estimated during modeling process, and
$X_2 - X_n$ = variables included in given SPF.

Table B24. Total Crash SPF for Lane and Shoulder Width on Tangents

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State 1 (1=Washington; 0=Illinois)	-0.3155	0.0427	-7.39	0.0000	-0.3992	-0.2319
State 1 (1=Ohio; 0=Illinois)	0.4170	0.0340	12.27	0.0000	0.3504	0.4836
11-ft lanes and 4-ft shoulders	-0.0057	0.0634	-0.09	0.9290	-0.1299	0.1186
11-ft lanes and 8-ft shoulders	-0.1140	0.0756	-1.51	0.1320	-0.2622	0.0342
12-ft lanes and 3-ft shoulders	-0.0794	0.0589	-1.35	0.1780	-0.1949	0.0360
12-ft lanes and 4-ft shoulders	-0.1359	0.0566	-2.40	0.0160	-0.2468	-0.0250
12-ft lanes and 8-ft shoulders	-0.1621	0.0558	-2.91	0.0040	-0.2715	-0.0528
log(AADT)	0.7858	0.0217	36.13	0.0000	0.7432	0.8284
Constant	-5.0209	0.1733	-28.98	0.0000	-5.3605	-4.6813
alpha (α)	0.4016	0.0219			0.3609	0.4469

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 3-ft shoulders.

Table B25. Fatal and Injury Crash SPF for Lane and Shoulder Width on Tangents

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State 1 (1=Washington; 0=Illinois)	0.2750	0.0677	4.06	0.0000	0.1423	0.4077
State 1 (1=Ohio; 0=Illinois)	0.5594	0.0554	10.09	0.0000	0.4508	0.6681
11-ft lanes and 4-ft shoulders	0.0147	0.1006	0.15	0.8840	-0.1826	0.2119
11-ft lanes and 8-ft shoulders	-0.4195	0.1268	-3.31	0.0010	-0.6679	-0.1711
12-ft lanes and 3-ft shoulders	-0.2288	0.0949	-2.41	0.0160	-0.4149	-0.0427
12-ft lanes and 4-ft shoulders	-0.1904	0.0885	-2.15	0.0310	-0.3638	-0.0170
12-ft lanes and 8-ft shoulders	-0.3291	0.0879	-3.74	0.0000	-0.5014	-0.1567
log(AADT)	0.9338	0.0365	25.57	0.0000	0.8622	1.0054
Constant	-7.7936	0.2945	-26.46	0.0000	-8.3708	-7.2164
alpha (α)	0.3639	0.0460			0.2840	0.4663

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 3-ft shoulders.

Table B26. Run-Off-Road Crash SPF for Lane and Shoulder Width on Tangents

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State 1 (1=Washington; 0=Illinois)	0.3578	0.0599	5.97	0.0000	0.2403	0.4752
State 1 (1=Ohio; 0=Illinois)	0.5174	0.0511	10.13	0.0000	0.4173	0.6175
11-ft lanes and 4-ft shoulders	-0.1984	0.0895	-2.22	0.0270	-0.3739	-0.0230
11-ft lanes and 8-ft shoulders	-0.3696	0.1084	-3.41	0.0010	-0.5820	-0.1572
12-ft lanes and 3-ft shoulders	-0.3096	0.0825	-3.75	0.0000	-0.4714	-0.1479
12-ft lanes and 4-ft shoulders	-0.3538	0.0779	-4.54	0.0000	-0.5065	-0.2011
12-ft lanes and 8-ft shoulders	-0.4941	0.0780	-6.33	0.0000	-0.6470	-0.3412
log(AADT)	0.6818	0.0323	21.14	0.0000	0.6186	0.7451
Constant	-5.3626	0.2558	-20.96	0.0000	-5.8640	-4.8612
alpha (α)	0.4130	0.0414			0.3393	0.5026

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 3-ft shoulders.

Table B27. Target Crash SPF for Lane and Shoulder Width on Tangents

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State 1 (1=Washington; 0=Illinois)	0.2492	0.0564	4.41	0.0000	0.1386	0.3598
State 1 (1=Ohio; 0=Illinois)	0.5613	0.0468	11.99	0.0000	0.4696	0.6531
11-ft lanes and 4-ft shoulders	-0.1999	0.0840	-2.38	0.0170	-0.3645	-0.0353
11-ft lanes and 8-ft shoulders	-0.3571	0.1010	-3.53	0.0000	-0.5551	-0.1590
12-ft lanes and 3-ft shoulders	-0.2961	0.0772	-3.84	0.0000	-0.4473	-0.1449
12-ft lanes and 4-ft shoulders	-0.3722	0.0731	-5.09	0.0000	-0.5155	-0.2289
12-ft lanes and 8-ft shoulders	-0.4366	0.0726	-6.02	0.0000	-0.5789	-0.2944
log(AADT)	0.7629	0.0302	25.24	0.0000	0.7037	0.8222

Constant	-5.8411	0.2407	-24.27	0.0000	-6.3129	-5.3694
alpha (α)	0.3699	0.0349			0.3075	0.4450

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 3-ft shoulders.

Table B28. Total Crash SPF for Lane and Shoulder Width on Curves

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State (1=Washington; 0=Ohio)	-0.7749	0.0829	-9.35	0.0000	-0.9374	-0.6124
11-ft lanes and 4-ft shoulders	0.0907	0.1429	0.63	0.5260	-0.1895	0.3709
11-ft lanes and 8-ft shoulders	-0.2105	0.1678	-1.25	0.2100	-0.5394	0.1184
12-ft lanes and 2-ft shoulders	-0.1230	0.1577	-0.78	0.4360	-0.4322	0.1862
12-ft lanes and 4-ft shoulders	-0.1343	0.1290	-1.04	0.2980	-0.3872	0.1186
12-ft lanes and 8-ft shoulders	-0.2745	0.1373	-2.00	0.0460	-0.5436	-0.0053
1/degree of curve	-0.1414	0.0789	-1.79	0.0730	-0.2961	0.0132
log(AADT)	0.7499	0.0505	14.85	0.0000	0.6509	0.8489
Constant	-3.8411	0.3975	-9.66	0.0000	-4.6202	-3.0620
alpha (α)	0.4690	0.0735			0.3449	0.6376

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 2-ft shoulders.

Table B29. Fatal and Injury Crash SPF for Lane and Shoulder Width on Curves

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State (1=Washington; 0=Ohio)	-0.3147	0.1346	-2.34	0.0190	-0.5786	-0.0509
11-ft lanes and 4-ft shoulders	0.1183	0.2150	0.55	0.5820	-0.3030	0.5396
11-ft lanes and 8-ft shoulders	-0.4534	0.2645	-1.71	0.0860	-0.9719	0.0650
12-ft lanes and 2-ft shoulders	-0.2828	0.2552	-1.11	0.2680	-0.7829	0.2174
12-ft lanes and 4-ft shoulders	-0.1789	0.1975	-0.91	0.3650	-0.5661	0.2083
12-ft lanes and 8-ft shoulders	-0.4176	0.2145	-1.95	0.0520	-0.8380	0.0028
1/degree of curve	-0.2503	0.1416	-1.77	0.0770	-0.5279	0.0272
log(AADT)	0.7275	0.0758	9.60	0.0000	0.5790	0.8760
Constant	-4.9578	0.6036	-8.21	0.0000	-6.1409	-3.7748
alpha (α)	0.4940	0.1827			0.2393	1.0199

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 2-ft shoulders.

Table B30. Run-Off-Road Crash SPF for Lane and Shoulder Width on Curves

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State (1=Washington; 0=Ohio)	-0.2548	0.1203	-2.12	0.0340	-0.4906	-0.0190
11-ft lanes and 4-ft shoulders	0.1079	0.1839	0.59	0.5570	-0.2524	0.4683

11-ft lanes and 8-ft shoulders	-0.4617	0.2306	-2.00	0.0450	-0.9137	-0.0097
12-ft lanes and 2-ft shoulders	-0.0499	0.2030	-0.25	0.8060	-0.4478	0.3480
12-ft lanes and 4-ft shoulders	-0.1386	0.1683	-0.82	0.4100	-0.4684	0.1913
12-ft lanes and 8-ft shoulders	-0.5967	0.1904	-3.13	0.0020	-0.9699	-0.2235
1/degree of curve	-0.4179	0.1393	-3.00	0.0030	-0.6909	-0.1449
log(AADT)	0.6597	0.0677	9.74	0.0000	0.5270	0.7924
Constant	-3.9134	0.5347	-7.32	0.0000	-4.9614	-2.8653
alpha (α)	0.9188	0.1626			0.6494	1.2999

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 2-ft shoulders.

Table B31. Target Crash SPF for Lane and Shoulder Width on Curves

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
State (1=Washington; 0=Ohio)	-0.3881	0.1142	-3.40	0.0010	-0.6120	-0.1642
11-ft lanes and 4-ft shoulders	0.1193	0.1781	0.67	0.5030	-0.2297	0.4684
11-ft lanes and 8-ft shoulders	-0.4916	0.2250	-2.18	0.0290	-0.9326	-0.0506
12-ft lanes and 2-ft shoulders	-0.0548	0.1962	-0.28	0.7800	-0.4393	0.3296
12-ft lanes and 4-ft shoulders	-0.1484	0.1631	-0.91	0.3630	-0.4681	0.1712
12-ft lanes and 8-ft shoulders	-0.5529	0.1822	-3.03	0.0020	-0.9101	-0.1957
1/degree of curve	-0.3589	0.1275	-2.81	0.0050	-0.6089	-0.1090
log(AADT)	0.6733	0.0656	10.26	0.0000	0.5447	0.8019
Constant	-3.8550	0.5175	-7.45	0.0000	-4.8692	-2.8407
alpha (α)	0.9086	0.1494			0.6582	1.2542

Note: Baseline for lane and shoulder combinations is 11-ft lanes and 2-ft shoulders.

Combination of Intersection Skew Angle and Sight Distance Improvements

For this analysis, the team employed a cross-sectional modeling approach to estimate CMFs for the individual treatment effects as well as the combined treatment effect. The two individual treatment effects were defined as follows:

- Individual intersection sight distance (ISD) effect: available ISD of more than 1,320 ft compared to a baseline condition of 500 ft to 750 ft.
- Individual intersection angle effect: intersection angle of 85 degrees to 90 degrees compared to a baseline condition of 50 degrees to 75 degrees.

The combined treatment effect was defined as follows:

- Combined treatment effect: available ISD of more than 1,320 ft and intersection angle of 85 degrees to 90 degrees compared to baseline conditions for both.

The previous section described the general cross-sectional study design. Again, for this method to work, the two groups should be similar in all regards except for the feature of interest. To minimize differences among the groups, propensity score matching was employed, and multivariate regression models were used to estimate the safety effects of one feature while controlling for other characteristics that vary among sites.

Multivariate regression was used to develop a statistical relationship between the dependent variable and a set of predictor variables. In this case, crash frequency was the dependent variable of interest and several predictor variables were considered, including ISD, intersection angle, and other roadway and operational characteristics. Coefficients were estimated during the modeling process for each of the predictor variables. The coefficients represent the expected change in the dependent variable (crash frequency) due to a unit change in the predictor variable, all else being equal.

The current state-of-the-practice for developing crash prediction models is to assume a log-linear relationship between crash frequency and site characteristics. GLM techniques were applied to develop the models, and a log-linear relationship was specified using a negative binomial error structure. The negative binomial error structure also has advantages over the Poisson distribution in that it allows for over-dispersion of the variance that is often present in crash data.

There are several potential sources of bias in the development of crash prediction models. The following is a list of potential sources of bias with an explanation of how they were addressed:

- *Selection of appropriate functional form:* Functional form relates to both the overall form of the model and the form of each independent variable. The current state-of-the-practice was used for the overall form of the model (i.e., log-linear relationship), and exploratory data analysis techniques were used to identify an appropriate form for each predictor.
- *Correlation among independent variables:* Correlation refers to the degree of association among variables. A high degree of correlation among the predictor variables makes it difficult to determine a reliable estimate of the effects of specific predictor variables. The correlation matrix was examined to determine the extent of correlation among independent variables, and used to prioritize variables for inclusion.
- *Over-fitting of prediction models:* Over-fitting is related to the law of diminishing returns. At some point, it is not worth adding any more independent variables to the model because they do not significantly improve the model fit. Over-fitting also increases the opportunity to introduce correlation in the model. Several combinations of predictor variables were considered, and relative goodness-of-fit (GOF) measures were employed to penalize models with more estimated parameters.

The multivariate models were developed by identifying base models with traffic volume only, exploring the effects of adding other predictor variables to the models, and then selecting the final model. Having developed the base models for each crash type (traffic volume only), additional variables were considered. Once a variable was included in the model, the estimated parameters and associated standard errors were examined to determine the following:

- Is the direction of effect (i.e., expected decrease or increase in crashes) in general agreement with expectations?
- Does the magnitude of the effect seem reasonable?
- Are the parameters of the model estimated with statistical significance?
- Does the estimated over-dispersion parameter improve significantly?

The remainder of this section presents the SPFs developed for each focus crash type (i.e., total target, fatal and injury target, and right-angle crashes). The following is the general form of the SPFs.

Equation B7

$$SPF = e^{\text{constant} + \beta1*\log(\text{AADT Major}) + \beta2*\log(\text{AADT Minor}) + \beta3*X3 + \ldots + \beta n*Xn}$$

Where,

length = segment length (miles),

Constant = constant estimated during modeling process,

Log(AADT Major) = natural log of major road traffic volume,

Log(AADT Minor) = natural log of minor road traffic volume,
$\beta_1 - \beta_n$ = Coefficients estimated during modeling process, and
$X_3 - X_n$ = variables included in given SPF.

Table B32. Total Target Crash SPF for ISD and Intersection Angle

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT Major)	0.7008	0.1555	4.51	0.0000	0.3960	1.0055
log(AADT Minor)	0.5475	0.1285	4.26	0.0000	0.2958	0.7993
Approaches (1=4-legged; 0=3-legged)	0.3956	0.2298	1.72	0.0850	-0.0547	0.8459
Direction (1=left; 0=right)	0.5978	0.2137	2.80	0.0050	0.1790	1.0166
Lane Width (1=12+ ft; 0 otherwise)	-0.7026	0.2210	-3.18	0.0010	-1.1358	-0.2694
State 1 (1=North Carolina; 0=Ohio)	-0.7008	0.2796	-2.51	0.0120	-1.2489	-0.1528
State 2 (1=Washington; 0=Ohio)	-0.9531	0.3114	-3.06	0.0020	-1.5635	-0.3428
ISD = 500 – 750	0.7862	0.2648	2.97	0.0030	0.2673	1.3052
Intersection Angle = 50 – 75	0.8812	0.2838	3.11	0.0020	0.3250	1.4374
ISD and Intersection Angle Combination	0.7573	0.4512	1.68	0.0930	-0.1269	1.6416
Constant	-11.6491	1.6827	-6.92	0.0000	-14.9470	-8.3511
alpha (α)	2.0650	0.4632			1.3304	3.2053

Table B33. Fatal and Injury Target Crash SPF for ISD and Intersection Angle

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT Major)	0.6785	0.2066	3.28	0.0010	0.2737	1.0834
log(AADT Minor)	0.3882	0.1581	2.46	0.0140	0.0785	0.6980
Direction (1=left; 0=right)	0.7111	0.2869	2.48	0.0130	0.1488	1.2733
State 1 (1=North Carolina; 0=Ohio)	-1.4426	0.3640	-3.96	0.0000	-2.1560	-0.7292
State 2 (1=Washington; 0=Ohio)	-1.2501	0.3802	-3.29	0.0010	-1.9953	-0.5050
ISD = 500 – 750	1.3023	0.3732	3.49	0.0000	0.5708	2.0338
Intersection Angle = 50 – 75	1.5540	0.3803	4.09	0.0000	0.8087	2.2993
ISD and Intersection Angle Combination	0.1944	0.8343	0.23	0.8160	-1.4408	1.8296
Constant	-11.3587	2.2317	-5.09	0.0000	-15.7327	-6.9847
alpha (α)	2.4519	0.8078			1.2855	4.6766

Table B34. Right Angle Crash SPF for ISD and Intersection Angle

Variable	Coefficient	Standard Error	Z-score	P-value	Lower 95% Conf. Int.	Upper 95% Conf. Int.
log(AADT Major)	0.6978	0.2243	3.11	0.0020	0.2581	1.1375
log(AADT Minor)	0.7770	0.1976	3.93	0.0000	0.3897	1.1642
Approaches (1=4-legged; 0=3-legged)	1.0985	0.3521	3.12	0.0020	0.4083	1.7886
Direction (1=left; 0=right)	0.5158	0.3059	1.69	0.0920	-0.0836	1.1153
Lane Width (1=12+ ft; 0 otherwise)	-1.1093	0.3272	-3.39	0.0010	-1.7506	-0.4680
State 1 (1=North Carolina; 0=Ohio)	-0.9164	0.3826	-2.40	0.0170	-1.6663	-0.1665
State 2 (1=Washington; 0=Ohio)	-2.1091	0.5114	-4.12	0.0000	-3.1114	-1.1068
ISD = 500 – 750	1.3293	0.4270	3.11	0.0020	0.4923	2.1662
Intersection Angle = 50 – 75	1.6804	0.4408	3.81	0.0000	0.8164	2.5443
ISD and Intersection Angle Combination	1.9234	0.6110	3.15	0.0020	0.7259	3.1210
Constant	-14.4170	2.5796	-5.59	0.0000	-19.4729	-9.3610
alpha (α)	3.2530	0.8777			1.9170	5.5201

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