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Statistical Analysis of Safety Improvements and Integration into Project Design Process

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16. Abstract

RoadHAT is a tool developed by the Center for Road Safety and implemented for the INDOT safety management practice to help identify both safety needs and relevant road improvements. This study has modified the tool to facilitate a quick and convenient comparison of various design alternatives in the preliminary design stage for scoping small and medium safety-improvement projects. The modified RoadHAT 4D incorporates a statistical estimation of the Crash Reduction Factors based on a before-and-after analysis of multiple treated and control sites with EB correction for the regression-to-mean effect. The new version also includes the updated Safety Performance Functions, revised average costs of crashes, and the comprehensive table of Crash Modification Factors—all updated to reflect current Indiana conditions. The documentation includes updated Guidelines for Roadway Safety Improvements. The improved tool will be implemented at a sequence of workshops for the final end users and preceded with a beta-testing phase involving a small group of INDOT engineers.

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EXECUTIVE SUMMARY

Introduction

A recent FHWA audit of INDOT's highway safety programs and procedures called for improvements in current procedures by incorporating safety considerations into the design of all INDOT and local projects. This outcome has prompted the INDOT Bridges and Highway Design Divisions to request the development of improved methods and software to evaluate the traffic safety implications of geometric design decisions. This report presents a study aimed to incorporate a systematic process for integrating the consideration of safety into project scoping and design.

The IHDSM, although calibrated to Indiana conditions in the recent JTRP study, is also suitable for large road projects; however, it requires designers' significant effort for preparing and entering the input. There is a need for a convenient tool for small and medium projects that can quickly and interactively facilitate a design process through to its completion.

This study was aimed to modify RoadHAT—a tool developed by the Purdue Center for Road Safety (CRS) and implemented for the INDOT safety management to facilitate a quick and convenient comparison of various design alternatives in the preliminary design stage for scoping small and medium safety-improvement projects.

Improvements

- Multiple design alternatives can be defined with different subsets of safety improvements, be saved, and then compared.
- Individual design changes of a segment roadway may begin and end anywhere inside a considered segment.
- Target crashes are introduced for each countermeasure as a percent of crashes at three levels of crash severity to make the analysis versatile and more accurate.
- The use of target crashes through a percent of all crashes at various severity levels enabled utilization of the existing safety performance functions in economic and before-and-after evaluation.
- Before-and-after studies of multiple treated and control sites can be facilitated with the improved tool.
- The statistical significance of safety improvement is estimated at the user-selected significance level.
- A provision for reading the crash location data allows the crash-countermeasure assignments made by the tool to considerably reduce the end-user's effort.
- Additional RoadHAT reports have been added for each design alternative, their comparison, and before-and-after studies.
- The Guidelines for Roadway Safety Improvements, Crash Reduction Factors, and Safety Performance Functions are updated.

Implementation

The RoadHAT 4D is a computer software developed in close collaboration with INDOT users. The project produced a modified RoadHAT tool with embedded documentation to help the end-user. Incorporation of the safety component in the early stage of design and post-construction evaluation will be supported with a sequence of workshops organized by the Business Owner and delivered by the Purdue CRS research team.

After the beta-testing phase, the developed tool will be distributed internally among INDOT units. The Purdue CRS will be involved in the RoadHAT 4D implementation by providing requested help, collecting the users' feedback, and implementing the recommendations.

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1. INTRODUCTION

The Fixing America's Surface Transportation (FAST) Act established regulations that require state departments of transportation (DOTs) to analyze and report the resulting safety performance of traffic safety improvement projects that were previously constructed and funded under the Highway Safety Improvement Program (HSIP). The purpose of the federal regulation is to strive for superior decision making in the allocation of highway safety funds to reduce the incidence of crashes resulting in fatalities and severe injuries. Prior to federal fiscal year 2018, state DOT reporting of post construction safety performance was largely voluntary. The INDOT Office of Traffic Safety has undertaken comparative "before/after" safety performance studies of previously completed HSIP projects; however, staff's current ability to calculate and report statistically significant analyses results is limited.

An appropriate methodology for the evaluation of traffic safety improvement projects is essential to identify the effectiveness of the implemented improvements or countermeasures and to quantify its benefits. A recent FHWA audit of INDOT's highway safety programs and procedures called for improvements in current procedures for incorporating safety considerations into the design of all INDOT and local projects. This outcome has prompted the INDOT Bridges and Highway Design Divisions to request development of improved methods and software to evaluate the traffic safety implications of geometric design decisions. This report presents a study aimed to incorporate a systematic process for integrating the consideration of safety into project scoping and design applied to existing roads that are selected for safety improvements.

The IHDSM, although calibrated to the Indiana conditions in the recent JTRP study (Tarko et al., 2018) is suitable for large road projects in mind and it requires designers' significant effort for preparing and entering the input. Yet, it does not support sequential decision-making in the course of design but rather it facilitates a selection of the most promising alternative from several alternatives already designed. Thus, there is a need for a convenient tool for small and medium projects that could facilitate a way to quickly and interactively review design alternatives within a design process up to its completion.

RoadHAT is a tool developed by the Center for Road Safety and successfully implemented to the INDOT safety management practice to help identify both the safety needs and the relevant road improvements. It does not allow a quick and convenient comparison of various preliminary design alternatives to facilitate projects scoping.

The applied research study reported in this document modified the existing RoadHAT 3 tool to incorporate its statistical analysis capability as part of post construction performance evaluations, principally Empirical-Bayes (EB) or some other statistical analysis methodology for various safety improvements on state and local highways. This software tool is supposed to support job scoping in the preliminary design stage for small and medium safety-improvement projects and to aid analyzing the post-construction performance of safety improvement projects. The envisioned new components were embedded in the existing RoadHAT 3 software as RoadHAT 4D. The new version also includes the updated Safety Performance Functions, revised average costs of crashes, and the comprehensive table of Crash Modification Factors updated to reflect the current Indiana conditions.

2. RESEARCH OBJECTIVES AND SCOPE

The scope of work includes analysis of the methodologies used in other states by studying the existing publications, research reports, and guidelines. The information relevant to the project topic will be compiled to determine the best practice process for both the evaluation of traffic safety improvement projects and for estimating the safety implications of geometric design decisions.

A computer application will be developed to incorporate statistical analysis capability as part of post construction performance evaluations. Performance measures will estimate safety benefits in terms of reduction in number of crashes and long term economic impacts.

The primary research objectives of the proposed project are as follows:

1. Develop a process for integrating road safety consideration into project scoping and design.
2. Develop a methodology to evaluate traffic safety improvement projects and to update and apply CMFs when multiple countermeasures are proposed.
3. Expand the existing RoadHAT software by integrating the modules developed in Tasks 1 and 2.

3. CONCEPT OF REVISED ROADHAT

The new version—RoadHAT 4D—supports scoping of safety project for existing roads by allowing convenient generation of design alternatives at the level of detail possible before the preliminary design stage. A *project alternative* is defined with the existing road geometry and traffic control supplemented with the proposed safety countermeasures—changes of the road geometry and traffic control aimed to improve safety. Thus, the default reference alternative is by default do-nothing option. It is not explicitly represented among the alternatives. Instead, all explicitly stated alternatives are compared to the do-nothing alternative by estimating the safety benefits and the project costs.

An alternative is created in Form 5 by adding one or more countermeasures. Each countermeasure is defined with the following elements:

- countermeasure name, possibly including a short description,

- part of road segment affected by the countermeasures (start and end points, only for segments),
- crash reduction factors by severity (three levels),
- percent of crashes that are affected at each severity level (target crashes),
- countermeasure capital cost,
- change in the maintenance cost, and
- salvage value.

The cost components can be entered for every countermeasure if such cost assignments to specific countermeasures are possible. Otherwise, a dummy countermeasure with zero Crash Reduction Factors can be entered together with the capital cost, change in the maintenance cost, and salvage value applicable to multiple countermeasures. More than one dummy countermeasure may be used. The name and description of the dummy countermeasure may state which countermeasures are included in the cost components.

New countermeasures can be added and existing countermeasures may be copied or deleted. A copied countermeasure may be edited to create a new countermeasure that is not much different from the existing one (for example, different only by affected part of the segment).

Any project alternative can be saved under its own name. Any saved alternative can be read for modifications and saved under its own name or under a differed name to add a new alternative to the already saved ones.

Calculated economic components include the following:

- saved crashes by severity,
- annualized cost of all crashes saved,
- annualized cost of the project,
- annualized net benefit, and
- B/C ratio.

Summary of the results of all saved alternatives are available for comparison in Form 6. User selects alternatives for comparing side by side from a list of all available alternatives. Any alternative already displayed for comparison can be removed. The comparison includes the alternative names, list of alterative names, and the economic components. A report saved by the user includes all the displayed alternatives.

Form 7 is added to facilitate the estimation of the Crash Modification Factors and to evaluate the effectiveness of the safety project in improving safety. The user may enter multiple roads with similar safety project applied to these roads. In addition, the user has an option to include control site in the analysis. A control site is a road without any road changes during the analysis period and similar to the road treated with safety countermeasures. A control site accounts for any overall changes in safety not related to the road improvements and caused by changes in traffic composition, weather, vehicle design, etc.

The effectiveness of the safety improvements are represented with the magnitude of crash reduction and with the statistical significance of this reduction. A statistically significant crash reduction has small probability that the observed reduction was random and not systematic.

4. PREDICTING SAFETY BENEFITS OF ROAD IMPROVEMENTS

4.1 Intersections

Safety performance function (SPF) for an intersection is:

$$a = kQ_1^{\gamma_1} Q_2^{\gamma_2} \text{ (crashes/year)}$$

And the EB estimate of the expected annual number of crashes is:

$$a_{EB} = \frac{C + 1/\alpha}{Y + 1/(\alpha a)}$$

where: a_{EB} is EB-estimate of the expected number of crashes at the intersection (crashes/year), C is the number of crashes during Y years, Q_1 and Q_2 are the AADTs on the major and minor roads in (1000s veh/h), k,γ_1,γ_2 are parameters, and a is over-dispersion.

The number of saved crashes of certain severity with the countermeasures applied at intersections is:

$$b = a_{EB} CRF$$

with Crash Reduction Factor CRF, that represents multiple safety countermeasures applied at the intersection, being calculated as:

$$CRF = 100 \cdot \left[1 - \Pi_{j=1}^{n}\left(1 - \frac{PT_j}{100} \cdot \frac{CRF_j}{100}\right)\right]$$

where:

CRF= combined Crash Modification Factor representing the effect of all countermeasures applied at the intersection,

PT_j= percent of crashes of certain severity are target crashes for countermeasure j,

CRF_j= Crash Reduction Factor of countermeasure j.

4.2 Segments

The total number of crashes on the segment C and the segment length is L. A safety performance function (SPF) for a segment is:

$$a = kL^{\beta} Q^{\gamma}$$

where: a is the expected number of crashes on the segments (crashes/year), L is the segment length (mi), Q is the AADT in (1000s veh/h), k,β,γ are parameters, and a is over-dispersion.

The total number of crashes on the segment C. Let the segment be divided into sub-segments of lengths: l_1,l_2, and lm with crash counts: c_1,c_2, and c_m. The SPF-based expected number of crashes on any sub-segment i is:

$$a_i = \left(\frac{l_i}{L}\right) kL^{\beta} Q^{\gamma} = kl_i L^{\beta-1} Q^{\gamma}$$

and the *initial* EB-based expected number of crashes a_{Bi} on any sub-segment i is:

$$a_{Bi} = \frac{c_i + 1/\alpha}{1 + 1/(\alpha a_i)}$$

Where $c_i =$ is the number of crashes on sub-segment i.

The EB-based total number of crashes on the segment is:

$$a_{EB} = \frac{C + 1/\alpha}{1 + 1/(\alpha a)}$$

The *adjusted* EB-based expected number of crashes a_{EBi} on any sub-segment i is:

$$a_{EBi} = a_{EB} \frac{a_{Bi}}{\sum_i a_{Bi}}$$

$$CRF_i = 100 \cdot \left[1 - \Pi_{j=1}^{j=n_i}\left(1 - \frac{PT_{i,j}}{100} \cdot \frac{CRF_{i,j}}{100}\right)\right]$$

where:

CRF_i= combined Crash Modification Factor representing the effect of all countermeasures applied on sub-segment i,

$PT_{i,j}$= percent of crashes of certain severity on sub-segment i that are target crashes for countermeasure j,

$CRF_{i,j}$= Crash Reduction Factor of countermeasure j applied on segment i.

The number of crashes of certain severity saved on the entire segment is:

$$b = \sum_{i=1}^{m} a_{EBi} CRF_i$$

When the distribution of crashes among sub-segments is not known, the simplest approximation is based on the assumption that the crashes are distributed in proportion of the sub-segment lengths. Thus:

$$b = \sum_{i=1}^{m} \left(\frac{l_i}{L}\right) a_{EB} CRF_i$$

5. ESTIMATING CRASH REDUCTION FACTORS

The effectiveness of a safety project should be reevaluated after its implementation to provide feedback to the safety management process. This feedback helps improve future decision about specific safety improvement and prediction of their effectiveness. The post implementation study uses crash data collected before and after the project is implemented. Although the recommended periods before and after the implementation are three years for each period, longer periods increase the confidence of the results and should be considered. In all cases, the periods should be multiples of full years to eliminate the undesirable effect of seasonal variations of crashes. Other data needed for a post-implementation study include actual project costs, annual maintenance costs, traffic growth rate, and average daily traffic volumes.

The outcome from the post implementation study includes the following: updated crash reduction factor (CRF) and the measures of economic effectiveness (B/C ratio, net annual benefits, and present worth of total net benefit). The method of analysis is the same as presented in chapter 6. The difference is the updated inputs. The following sections present the most difficult component of post implementation study—estimating and updating crash reduction factors. The method is introduced gradually by consideration of a single site. Then, a control site is added to account for safety factors other than the safety project. Next, a case of multiple treated and control sites is presented. Finally, a method of combining the new crash reduction factors with the existing one is shown.

5.1 Single Location

Crash Reduction Factors are used in calculating benefits provided by a safety project as the percent of original crashes reduced by the implementation of the safety project. The crash reduction factor for the project is calculated using crash reported before and after implementing the safety project. Expected crash frequency a_{0A} in the period after implementation of a safety project, *had the safety project not been implemented*, is calculated to account for the "regression-to-mean effect" and for the change in traffic volume. The available safety performance functions estimate the frequency of all crashes at different levels of severity while some CRFs are applicable only to, so-called, target crashes to account for the fact that a considered countermeasure affects only some type of crashes. For example, installing a median barrier reduces head-on collisions. This is accounted for in the calculation with the percent of target crashes (*PT*) that is used to reduce the crash frequencies estimated with safety performance functions to the frequency of target crashes.

The crash reduction factor for the implemented safety project CRF_2 and its standard deviation are calculated. Crash reduction factors are estimated for all crashes, incapacitating injury and fatal (NI) crashes, non-incapacitating injuries (NI) crashes, and property damage only (PD) crashes separately.

$$a_{0A} = \frac{\frac{1}{D} + C_B}{\frac{100}{D \cdot PT \cdot a_B} + Y_B} \cdot \left(\frac{a_A}{a_B}\right)$$

$$a_{1A} = \frac{C_A}{Y_A}$$

$$var\ a_{0A} = \frac{\frac{1}{D} + C_B}{\left(\frac{100}{D \cdot PT \cdot a_B} + Y_B\right)^2} \cdot \left(\frac{a_A}{a_B}\right)^2$$

$$var\ a_{1A} = \frac{C_A}{Y_A^2}$$

$$CRF_2 = 100\left(1 - \frac{a_{1A}}{a_{0A}}\right)$$

$$SD_2 = 100\sqrt{\frac{var\ a_{1A}}{a_{0A}^2} + \frac{a_A^2\ a_{0A}}{a_{0A}^4}}$$

where:

a_{0A}= best estimate of the target crash frequency in the period after the implementation of safety project, had the safety project not been implemented, this estimate is the combination of crash counts and the result obtained with a safety performance function,

a_{1A}= target crash frequency estimate for the period after the project implementation, this estimate is based on crashes that occurred at the improved site,

a_A= crash frequency (total of target and non-target crashes) calculated with a safety performance function and for traffic representing the after-implementation period,

a_B= crash frequency (total of target and non-target crashes) calculated with a safety performance function and for traffic representing the before-implementation period,

C_A= number of reported target crashes (affected by the countermeasure) that occurred during the period after the implementation of safety project,

C_B= number of target crashes that occurred during the period before the implementation of safety project,

CRF_2= crash reduction factor estimate, in percent,

D= over-dispersion parameter associated with the safety performance function used to calculate a_A and a_B

PT= percent of crashes that are affected by the countermeasure (target crashes), in percent,

SD_2= standard deviation of the crash reduction factor estimate for the implemented safety project, in percent,

$var\ a_{0A}$= variance of a_{0A} estimate,

$var\ a_{1A}$= variance of a_{1A} estimate,

Y_B= number of before-implementation years with crash data, and

Y_A= number of after-implementation years with crash data.

5.2 Estimating Cash Reduction Factors Using a Control Site

In order to account for unknown factors that may cause a change in the number of crashes after implementation of the safety project, crash reduction factors are calculated using a control group, which consists of locations that have characteristics similar to locations where the safety project is implemented, but at these locations the safety project is not implemented. The expected number of crashes per year in the period after implementation of the safety project assuming no road improvement, a_{0A}, and the number of crashes per year during the period after the implementation of the safety project, a_{1A}, are calculated for the treated sites. The same equations are used to calculate a'_{0A} and a'_{1A} for the control site. The before and after periods for the control site should match the corresponding period for the treated site. A, so-called, crash reduction θ is the ratio of a_{1A} and a_{0A}:

$$\theta = \frac{a_{1A}}{a_{0A}}$$

The variance of θ estimate is:

$$var\ \theta = \left(\frac{1}{a_{0A}}\right)^2 \cdot var\ a_{1A} + \left(\frac{a_{1A}}{a_{0A}^2}\right)^2 \cdot var\ a_{0A}$$

The corresponding ratio θ' is calculated for the control sites using a'_{1A} and. a'_{0A} Its variance of θ' estimate for the control site is calculated with the same equation of the variance of θ estimate.

The crash reduction factor CRF_2, which includes the adjustment for safety factors other than the safety project and the change in traffic volume, is estimated as follows:

$$CRF_2 = 100\left(1 - \frac{\theta}{\theta'}\right)$$

The variance of the CRF_2 estimate is calculated as follows:

$$SD_2 = 100\sqrt{\left(\frac{1}{\theta'}\right)^2 \cdot var\ \theta + \left(\frac{\theta}{\theta'^2}\right)^2 \cdot var\ \theta'}$$

where:

θ= crash reduction at the location with treated group,

$var\ \theta$= variance of θ estimate,

θ'= crash reduction at the location with control group,

$var\ \theta'$= variance of θ' estimate,

CRF_2= crash reduction factor after implementing the safety project, in percent, and

SD_2= standard deviation of the crash reduction factor for the implemented safety project, in percent.

5.3 Estimating Crash Reduction Factors Based on Multiple Locations

Crash reduction factors are key inputs to estimating safety benefits. They should be as accurate as possible. One of the methods of improving accuracy and precision of crash reduction factors estimates is using multiple treated and control sites. It is required that all the treated sites included in the analysis undergo the same type of improvement. The control group of sites where no improvements are implemented should be in the same geographical area as the treated sites. The average before periods for the treated and control sites should be the similar. The same is required for the average after period.

Modernization of different sites takes place in different years. To preserve the adjusting capabilities of the control sites, each of the treated sites should have at least one control site of the same type and similar characteristics, if possible. The treated and corresponding control sites should be similar and have the same before periods and the same after periods.

The idea of analyzing multiple sites is to aggregate the treated sites and the control sites into two single entities. This aggregation allows using the equations already developed for single sites. The first step is to estimate the annual number of crashes and the variance of this estimate for each treated and control site for the before and after periods using equation presented above. Then, the annual frequencies and their variances are summed up to obtain singles values representing the treated group of sites. The same aggregation operation is done for the control group. After this aggregation, the estimation method applicable to a single treated site with a single control site presented above is used.

$$a_{1A} = \sum_i a_{Ai}$$

$$var\ a_{1A} = \sum_i var\ a_{1Ai}$$

$$a_{0A} = \sum_i a_{0Ai}$$

$$var\ a_{0A} = \sum_i var\ a_{0Ai}$$

The above summation over multiple sites is done for crashes at each of the three severity levels, (incapacitating IN, non-incapacitating NI, and property damage only PD) or for all crashes regardless of the severity. Thus, the obtained estimates: a_{1A}, $var\ a_{1A}$, a_{0A}, $var\ a_{0A}$, apply to each of the three severity levels or two all crashes.

6. UPDATING CRASH REDUCTION FACTORS

This section describes the calculations of the crash reduction factor applicable to crash counts at three severity levels and to all crash count as well. The calculated values are then combined with the existing crash reduction factors (if available) to obtain the best estimates of the crash reduction factors.

Let CRF_1 stand for the old crash reduction factor taken from Appendix C, while CRF_2 is calculated. The updated crash reduction factor, CRF, is calculated using the CRF_1 and CRF_2 estimates and their standard deviations SD_1 and SD_2 respectively:

$$CRF = \frac{SD_1^2 \cdot CRF_2 + SD_2^2 \cdot CRF_1}{SD_1^2 + SD_2^2}$$

where:

CRF= updated crash reduction factor, percent,

SD_1= standard deviation of the old crash reduction factor estimate (assume 25% if not available), in percent, and

SD_2= standard deviation of the new crash reduction factor estimate for the implemented safety project, in percent.

The standard deviation of the updated crash reduction factor is calculated with standard deviations SD_1 and SD_2, as follows:

$$SD = \sqrt{\frac{SD_2^4 \cdot SD_1^2 + SD_1^4 \cdot SD_2^2}{SD_1^2 + SD_2^2}}$$

where: SD_1 and SD_2 are the standard deviations of the old and updated crash reduction factors. The calculated SD becomes SD_1 when the crash reduction factor is updated again.

7. STATISTICAL SIGNIFICANCE OF CRASH REDUCTION

The agency may want to test the statistical significance of the effectiveness of a safety project to determine whether the reduction in crashes is large enough to reject the possibility that the reduction was caused solely by random fluctuations of crashes. A one-tail test is used to decide if the obtained crash reduction factor is significantly larger than zero. The estimate of the crash reduction factor is assumed to be normally distributed. The recommended significance levels are 1%, 5%, and 10%. The default value is 10%.

The significance for the safety change is performed at a user selected significance level. The choice of significance level depends on the project size (cost). A significance level of 5% can be used for large and expensive projects, while 10% may be used for small projects. The 10% significance level is considered typical in post-implementation studies.

Table 7.1 helps determine whether the reduction in crashes is significant at 1%, 5%, 10% significance level. If normalized value Z=CRF/SD is larger than the critical value Z_c, then the safety improvement is statistically significant at the selected level of significance.

TABLE 7.1
Critical Value Z_c

Significance Level (%)	Critical Value Z_c
1	2.33
5	1.65
10	1.28

8. CLOSURE

The project has produced a modified RoadHAT 4D tool with companion user's manual. The user manual is embedded in the installation package and available via a *Help* link included in each form. The manuals first page provides links to all parts, elements, and terms of the tool. A revised version of the Guidelines are also included to introduce and help interpret of the elements of the safety management concepts.

Incorporation of the safety component in the early stage of design should increase the effectiveness of the project in reducing the frequency and severity of crashes. The second component of the project: post-construction evaluation, should have two-fold benefit.

1. The tool confirms which projects were successful and why. This feedback may help refocus future investments on projects that have a higher chance of being successful, thus leading to an additional improvement of road safety—the ultimate goal of all safety-related efforts.
2. The tool includes the components of the design methodology that should be tuned to produce better results. Specifically, two important improvements that need to be updated as needed are: (1) crash Modification Factors of road improvements, (2) costs of various road improvements.

REFERENCE

Tarko, A. P., Romero, M., Hall, T., & Sultana, A. (2018). *Updating the crash modification factors and calibrating the IHSDM for Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/03). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316646

APPENDICES

Appendix A. Updated Safety Performance Functions

Appendix B. Revised Crash Costs

Appendix C. Updated Crash Modification Factors

APPENDIX A. UPDATED SAFETY PERFORMANCE FUNCTIONS

Table A.1 State Intersections

Safety Performance Function	Over-dispersion
Signalized Urban State-State Intersection	
$a_{PD} = 8.3797 * 10^{-5} * AADT_1^{0.8077} * AADT_2^{0.4030} * e^{-0.4586*T\_indicator}$	0.5415
$a_{NI} = 1.7617 * 10^{-7} * AADT_1^{1.3787} * AADT_2^{0.1979}$	0.8926
$a_{FI} = 2.8870 * 10^{-5} * AADT_1^{0.7071} * AADT_2^{0.3709} * e^{-0.6066*T\_indicator}$	0.7130
Signalized Rural State-State Intersection	
$a_{PD} = 3.8929 * 10^{-3} * AADT_1^{0.3891} * AADT_2^{0.4310} * e^{-0.4349*T\_indicator}$	0.5547
$a_{NI} = 1.3378 * 10^{-5} * AADT_1^{1.1265}$	0.7754
$a_{FI} = 6.7616 * 10^{-2} * AADT_1^{0.2809} * e^{-0.7268*T\_indicator}$	0.8429
Unsignalized Urban State-State Intersection	
$a_{PD} = 2.2178 * 10^{-4} * AADT_1^{0.8481} * AADT_2^{0.2284} * e^{-0.7770*T\_indicator}$	0.7744
$a_{NI} = 1.0243 * 10^{-6} * AADT_1^{1.2145} * AADT_2^{0.1612} * e^{-0.4759*T_{indicator}}$	1.4455
$a_{FI} = 4.8134 * 10^{-5} * AADT_1^{0.7317} * AADT_2^{0.2595} * e^{-1.0369*T_{indicator}}$	1.2053
Unsignalized Rural State-State Intersection	
$a_{PD} = 2.6126 * 10^{-4} * AADT_1^{0.7880} * AADT_2^{0.3119} * e^{-0.5454*T\_indicator}$	0.6158
$a_{NI} = 1.1176 * 10^{-5} * AADT_1^{0.8521} * AADT_2^{0.3304} * e^{-0.1353*T\_indicator}$	0.9701
$a_{FI} = 6.6626 * 10^{-5} * AADT_1^{0.8546} * AADT_2^{0.1977} * e^{-0.6778*T\_indicator}$	0.7037
Signalized Urban State-Local Intersection	
$a_{PD} = 1.1165 * 10^{-2} * AADT_1^{0.6381} * e^{(-0.2427*T_{indicator}+0.4581*FC34_{indicator})}$	0.6537
$a_{NI} = 2.4457 * 10^{-4} * AADT_1^{0.8247} * e^{(-0.2935*T_{indicator}+0.3989*FC34_{indicator})}$	1.0684
$a_{FI} = 1.4198 * 10^{-3} * AADT_1^{0.6178} * e^{(-0.2738*T_{indicator}+0.3614*FC34_{indicator})}$	0.8425
Signalized Rural State-Local Intersection	
$a_{PD} = 1.1701 * 10^{-4} * AADT_1^{1.1212} * e^{(-0.1860*T_{indicator}+0.1525*FC34_{indicator})}$	0.6264
$a_{NI} = 1.5849 * 10^{-5} * AADT_1^{1.0969} * e^{(0.3911*FC34_{indicator})}$	0.8634
$a_{FI} = 1.3517 * 10^{-4} * AADT_1^{0.8833} * e^{(0.3985*FC34_{indicator})}$	0.9224
Unsignalized Urban State-Local Intersection	
$a_{PD} = 2.1986 * 10^{-4} * AADT_1^{0.9320} * e^{(-0.5273*T_{indicator}+0.8264*FC5_{indicator})}$	1.1808
$a_{NI} = 1.4185 * 10^{-6} * AADT_1^{1.2428} * e^{(-0.6126*T_{indicator}+0.7643*FC5_{indicator})}$	1.7019
$a_{FI} = 8.6677 * 10^{-6} * AADT_1^{1.0545} * e^{(-0.6311*T_{indicator}+0.8778*FC5_{indicator})}$	1.6761
Unsignalized Rural State-Local Intersection	
$a_{PD} = 1.8775 * 10^{-3} * AADT_1^{0.6820} * e^{(-0.3222*T_{indicator}+0.5506*FC5_{indicator})}$	1.0219
$a_{NI} = 3.1165 * 10^{-5} * AADT_1^{0.8953} * e^{(-0.5072*T_{indicator}+0.7877*FC5_{indicator})}$	1.7573
$a_{FI} = 2.0182 * 10^{-4} * AADT_1^{0.7492} * e^{(-0.5757*T_{indicator}+0.6593*FC5_{indicator})}$	1.4316
Interchange Intersection	
$a_{PD} = 3.3013 * 10^{-4} * AADT_1^{0.2240} * AADT_2^{0.7954}$	3.1278
$a_{BC} = 1.7931 * 10^{-4} * AADT_1^{0.1416} * AADT_2^{0.7171}$	3.0270
$a_{KA} = 1.0726 * 10^{-4} * AADT_1^{0.1416} * AADT_2^{0.7171}$	3.0270

Where:

a_{PD} = annual number of property-damage-only (PD) crashes

a_{NI} = annual number of non-incapacitating or possible (NI) crashes

a_{FI} = annual number of fatal or incapacitating (FI) crashes

$AADT_1$ = Annual Average Daily Traffic (AADT) along the major road

$AADT_2$ = Annual Average Daily Traffic (AADT) along the minor road

$T_{indicator}$ = binary indicator showing the presence of a T-intersection (1 if present, 0 otherwise)

$Urban_{indicator}$ = binary indicator showing the presence of a urban area (1 if present, 0 otherwise)

$FC3_{indicator}$ = binary indicator showing the presence of a principal arterial (1 if present, 0 otherwise)

$FC4_{indicator}$ = binary indicator showing the presence of a minor arterial (1 if present, 0 otherwise)

$FC5_{indicator}$ = binary indicator showing the presence of a major collector (1 if present, 0 otherwise)

$FC6_{indicator}$ = binary indicator showing the presence of a minor collector (1 if present, 0 otherwise)

$FC34_{indicator}$ = binary indicator showing the presence of a principal arterial or a minor arterial (1 if present, 0 otherwise)

$FC56_{indicator}$ = binary indicator showing the presence of a major collector or a minor collector (1 if present, 0 otherwise)

Table A.2 State Segments SPF

Safety Performance Function	Over-dispersion
Rural Two-Lane Segment	
$a_{PD} = 3.0512 * 10^{-3} * AADT^{0.7088} * Length^{1.0015} * e^{0.0712*Intden}$	0.9353
$a_{NI} = 2.6988 * 10^{-5} * AADT^{0.9734} * Length^{0.9893} * e^{0.0783*Intden}$	1.2975
$a_{FI} = 1.6622 * 10^{-4} * AADT^{0.8305} * Length^{0.9638} * e^{0.0480*Intden}$	1.0271
Rural Multilane Segment	
$a_{PD} = 3.0512 * 10^{-3} * AADT^{0.7088} * Length^{1.0015} * e^{0.0712*Intden}$	0.9353
$a_{NI} = 2.6988 * 10^{-5} * AADT^{0.9734} * Length^{0.9893} * e^{0.0783*Intden}$	1.2975
$a_{FI} = 1.6622 * 10^{-4} AADT^{0.8305} * Length^{0.9638} * e^{0.0481*Intden}$	1.0271
Rural Interstate Segment	
$a_{PD} = 3.1455 * 10^{-1} * AADT^{0.2869} * Length^{1.1279}$	0.4672
$a_{NI} = 1.1063 * 10^{-4} * AADT^{0.7746} * Length^{1.0224}$	0.4756
$a_{FI} = 3.4217 * 10^{-4} * AADT^{0.7283} * Length^{0.9005}$	0.3506
Urban Two-Lane Segment	
$a_{PD} = 2.7287 * 10^{-4} * AADT^{1.0054} * Length^{0.8660} * e^{0.0560*Intden}$	1.2984
$a_{NI} = 1.2714 * 10^{-6} * AADT^{1.3498} * Length^{0.8982} * e^{0.0567*Intden}$	1.9487
$a_{FI} = 1.1352 * 10^{-4} * AADT^{0.9099} * Length^{1.0374} * e^{0.0454*Intden}$	1.2893
Urban Multilane Segment	
$a_{PD} = 1.4748 * 10^{-4} * AADT^{1.0657} * Length^{0.9423} * e^{0.0443*Intden}$	1.3399
$a_{NI} = 5.7288 * 10^{-6} * AADT^{1.1792} * Length^{1.0151} * e^{0.0572*Intden}$	1.5400
$a_{FI} = 1.1864 * 10^{-4} * AADT^{0.8814} * Length^{1.0672} * e^{0.0554*Intden}$	1.3647
Urban Freeway Segment	
$a_{PD} = 4.8890 * 10^{-7} * AADT^{1.5733} * Length^{0.8828}$	0.3148
$a_{NI} = 6.3519 * 10^{-9} * AADT^{1.7090} * Length^{0.8907}$	0.4093
$a_{FI} = 2.6904 * 10^{-7} * AADT^{1.4256} * Length^{0.9725}$	0.2693
Rural Interchange Freeway Segment	
$a_{PD} = 9.9909 * 10^{-1} * AADT^{0.1699} * Length^{0.4908} * e^{(0.3710*DIMND+0.5954*CLOVER)}$	0.3879
$a_{NI} = 2.8675 * 10^{-4} * AADT^{0.7184} * e^{0.4660*CLOVER}$	0.1009
$a_{FI} = 3.7730 * 10^{-1} * AADT^{0.0702} * Length^{0.5405} * e^{0.4028*CLOVER}$	0.3900
Rural Interchange Non-freeway Segment	
$a_{PD} = 9.9894 * 10^{-4} * AADT^{0.7905} * e^{(0.6510*DIMND+0.4254*CLOVER)}$	1.4245
$a_{NI} = 4.6450 * 10^{-6} * AADT^{1.1507}$	2.1941
$a_{FI} = 9.2547 * 10^{-4} * AADT^{0.5960} * e^{0.3644*DIMND}$	1.0385
Urban Interchange Freeway Segment	
$a_{PD} = 9.8544 * 10^{-5} * AADT^{1.1344} * Length^{0.8282} * e^{-0.1919*DIMND}$	0.3869
$a_{NI} = 1.2281 * 10^{-6} * AADT^{1.2585} * Length^{0.6151} * e^{0.2291*CLOVER}$	0.2701
$a_{FI} = 1.0114 * 10^{-6} * AADT^{1.3269} * Length^{0.5967} * e^{0.2022*CLOVER}$	0.2285
Urban Interchange Non-freeway Segment	
$a_{PD} = 6.6648 * 10^{-3} * AADT^{0.6108} * Length^{0.7900} * e^{(1.5238*DIMND+0.7662*CLOVER)}$	1.6494
$a_{NI} = 2.8063 * 10^{-2} * AADT^{0.3079} * Length^{0.5705} * e^{0.9024*DIMND}$	1.5466
$a_{FI} = 7.6871 * 10^{-3} * AADT^{0.4663} * Length^{1.0147} * e^{0.5920*DIMND}$	2.6982
Ramps	
$a_{PD} = 1.7166 * 10^{-3} * AADT^{0.6550} + Length^{0.3181} * e^{(0.4199*URBAN+0.4112*OTHER)}$	5.1818
$a_{NI} = 5.1369 * 10^{-4} * AADT^{0.5362} + Length^{0.2629} * e^{(0.3629*LOOP+0.6036*OTHER)}$	6.2169
$a_{FI} = 4.4705 * 10^{-4} * AADT^{0.5362} + Length^{0.2629} * e^{(0.3629*LOOP+0.6036*OTHER)}$	6.2169

Where:

a_{FI} = annual number of fatal and incapacitating (FI) crashes

a_{NI} = annual number of non-incapacitating or possible (NI) crashes

a_{PD} = annual number of property damage only (PD) crashes

AADT = Annual Average Daily Traffic (AADT) along the segment

Length = Length of the segment in mile

Intden = no of minor intersection/segment length in mile

CLOVER = indicator variable for cloverleaf interchange (1 if present, 0 otherwise)

DIMND =indicator variable for diamond interchange (1 if present, 0 otherwise)

DIRECT = indicator variable for directional interchange (1 if present, 0 otherwise)

JUG = indicator variable for jug-handle interchange (1 if present, 0 otherwise)

TRUMPO = indicator variable for trumpet and other interchange (1 if present, 0 otherwise)

Diag = diagonal ramp

OTHER = other ramp (1 if other ramp type, 0 otherwise)

LOOP = loop ramp (1 if a loop ramp, 0 otherwise)

URBAN = urban indicator (1 if urban area, 0 otherwise).

APPENDIX B. REVISED CRASH COSTS

The average costs of crashes were estimated by calculating the individual crash cost considering the number of people killed/injured and the number of vehicles damaged. The averages of these costs then were obtained for the different types of segments/intersections/ramps.

The average cost of one fatality (K) is $10,562,000 and one incapacitating injury (A) is $1,155,000; the cost for a non-incapacitating (B) injury is considered as $318,000 and the cost of a possible injury (C) is considered as $147,000. On the other hand, for property damage only crashes (O), the average cost of a no injury is $11,900 and the cost per vehicle is $4,400 (source: National Safety Council, 2017, https://injuryfacts.nsc.org/all-injuries/costs/guide-to-calculating-costs/data-details/

The cost of a crash was calculated in the following way:

1. Calculate the cost of each crash

$$C = \$4{,}400 \cdot DV + CO \cdot \$11{,}900 + \$147{,}000 \cdot CP + \$318{,}000 \cdot BP + \$1{,}155{,}000 \cdot AP + \$10{,}562{,}000 \cdot KP$$

   where:
   C = crash cost ($),
   KP = number of fatalities (persons),
   AP = number of incapacitating injuries (persons),
   BP = number non-incapacitating injuries (persons),
   CP = number of possible injuries (person),
   CO = number of no injuries (person),
   DV = number of damaged vehicles.

2. Group crashes by road type and crash severity (FI, NI, PD)

3. Calculate the average cost of crash in each group *gr*

$$C_{gr} = \frac{\sum_{i \in I_{gr}} C_i}{N_{gr}}$$

   where:
   C_{gr} = average cost of crash in crash group *gr*,
   I_{gr} = indices of crashes that belong to crash group *gr*,
   C_i = cost of crash *i* calculated in step 1,
   N_{gr} = number of crashes in group *gr*.

Table B.1 Average Crash Costs for Segments

Road Type	Total Number			Total Cost of Crashes ($1000)			Average Crash Cost ($1000)		
	FI Crashes	NI Crashes	PD Crashes	FI Crashes	NI Crashes	PD Crashes	FI Crashes	NI Crashes	PD Crashes
Rural two-lane	3,472	2,018	24,137	8,323,525	709,064	672,589	2,397.3	351.4	27.9
Rural multilane	991	576	6,307	2,416,771	212,128	203,187	2,438.7	368.3	32.2
Rural interstate	1,190	596	10,885	2,774,074	197,299	343,561	2,331.2	331.0	31.6
Urban multilane	2,600	2,535	21,442	5,029,936	937,706	818,612	1,934.6	369.9	38.2
Urban two-lane	431	321	2,924	838,096	123,284	108,783	1,944.5	384.1	37.2
Urban freeway	667	372	6,271	1,260,023	122,819	224,268	1,889.1	330.2	35.8
Rural interchange freeway	262	144	2550	503,542	50,343	83,471	1,921.9	349.6	32.7
Rural interchange non-freeway	151	210	1634	311,239	82,983	58,862	2,061.2	395.2	36.0
Urban interchange freeway	1597	908	15896	2,925,187	295,615	595,634	1,831.7	325.6	37.5
Urban interchange non-freeway	217	236	2051	411,875	88,705	79,151	1,898.0	375.9	38.6
Ramps	322	370	4072	589,253	134,208	149,975	1,830.0	362.7	36.8
Rural Local Segments	1,871	1,273	18,673	3,806,561	409,326	493,949	2,034.5	321.5	26.5
Urban Local Segments	7,321	12,577	130,703	13,251,972	4,597,376	4,203,691	1,810.1	365.5	32.2

Note: The average crash costs increased considerably in 2016 when the comprehensive costs replaced the economic loss used in the previous years. The comprehensive unit costs are updated by NHTSA on regular basis and they tend to grow at rather high rate. Another source of the average crash costs increase was the 2016 modification of the Incapacitating Injury criterion. This effect was limited.

Table B.2 Average Crash Costs for Intersections

Element Type	Total Number			Total Cost of Crashes ($1000)			Average Crash Cost ($1000)		
	FI Crashes	NI Crashes	PD Crashes	FI Crashes	NI Crashes	PD Crashes	FI Crashes	NI Crashes	PD Crashes
Unsignalized Rural State-State	406	222	2,212	986,207	83,240	78,847	2,429.1	375.0	35.6
Signalized Rural State-State	160	113	1,016	386,617	41,875	39,300	2,416.4	370.6	38.7
Unsignalized Rural State-Local	3,173	1,857	18,419	7,391,022	725,030	577,816	2,329.3	390.4	31.4
Signalized Rural State-Local	396	389	3,277	842,940	170,139	131,224	2,128.6	437.4	40.0
Unsignalized Urban State-State	146	136	1,616	247,395	47,557	62,588	1,694.5	349.7	38.7
Signalized Urban State-State	438	510	4,730	809,973	188,501	193,684	1,849.3	369.6	40.9
Unsignalized Urban State-Local	2,903	2,856	24,642	5,644,291	1,044,027	950,486	1,944.3	365.6	38.6
Signalized Urban State-Local	2,342	3,336	24,750	4,150,564	1,251,049	1,020,012	1,772.2	375.0	41.2
Interchange Intersections	198	331	2,411	366,713	136,253	91,769	1,852.1	411.6	38.1
Urban Local Intersections	1,130	1,058	8,142	2,314,585	419,738	301,830	2,048.3	396.7	37.1
Rural Local Intersections	5,808	13,261	74,204	10,442,018	5,144,184	2,918,995	1,797.9	387.9	39.3

Note: The average crash costs increased considerably in 2016 when the comprehensive costs replaced the economic loss used in the previous years. The comprehensive unit costs are updated by NHTSA on regular basis and they tend to grow at rather high rate. Another source of the average crash costs increase was the 2016 modification of the Incapacitating Injury criterion. This effect was limited.

APPENDIX C. UPDATED CRASH MODIFICATION FACTORS

The following table presents the CRFs/CMFs for safety countermeasures that were identified as being the most suitable for Indiana based on the criteria presented in the Joint Transportation Research Program technical report, "Updating the Crash Modification Factors and Calibrating the IHSDM for Indiana" (Tarko et al., 2018). The table contains 82 safety countermeasures spanning 16 different categories. For each countermeasure, the applicable areas type (urban and/or rural), facility type, and CRF/CMF values for various crash types and severities are presented. Finally, the state(s) where each study was conducted and the corresponding reference are provided in the table.

Table C.1 Crash Modification Factors

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Access Management	Install two-way left-turn lane (TWLTL)	Rural	Two-lane highways	Total	36.0	0.640	AR, CA, IL, NC (29)
				Fatal/Injury	34.8	0.652	
				Rear-end	46.8	0.532	
Access Management	Replace TWLTL with raised median	Urban	Principal arterials; minor arterials; collectors	Total	23	0.77	NV (24)
				PDO	33	0.67	
				Fatal/Injury	21	0.79	
				Rear-end	19	0.81	
				Sideswipe	21	0.79	
				Angle	36	0.64	
				Head-on	47	0.53	
Access Management	Reduce driveway density by 1 driveway per mile[1]	Rural	Two-lane highways	Total	2.3	0.977	TX (11)
			Four-lane highways	Total	0.4	0.996	
Access Management	Reduce driveway density by 2 driveways per mile[1]	Rural	Two-lane highways	Total	4.5	0.955	TX (11)
			Four-lane highways	Total	0.7	0.993	
Access Management	Reduce driveway density by 3 driveways per mile[1]	Rural	Two-lane highways	Total	6.7	0.933	TX (11)
			Four-lane highways	Total	1.1	0.989	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Access Management	Reduce driveway density by 5 driveways per mile[1]	Urban	Principal arterials, minor arterials, or collectors with raised medians	Total	4.7	0.953	NV (24)
				PDO	3.5	0.965	
				Fatal/Injury	2.9	0.971	
				Rear-end	1.5	0.985	
				Angle	4.3	0.957	
			Principal arterials, minor arterials, or collectors with TWLTLs	Total	4.4	0.956	
				PDO	4.6	0.954	
				Fatal/Injury	1.3	0.987	
				Rear-end	3.8	0.962	
				Angle	4.1	0.959	
Access Management	Reduce driveway density by 10 driveways per mile[1]	Urban	Principal arterials, minor arterials, or collectors with raised medians	Total	9.2	0.908	NV (24)
				PDO	6.9	0.931	
				Fatal/Injury	5.7	0.943	
				Rear-end	3.0	0.970	
				Angle	8.3	0.917	
			Principal arterials, minor arterials, or collectors with TWLTLs	Total	8.6	0.914	
				PDO	9.0	0.910	
				Fatal/Injury	2.6	0.974	
				Rear-end	7.4	0.926	
				Angle	8.1	0.919	
Access Management	Reduce driveway density by 15 driveways per mile[1]	Urban	Principal arterials, minor arterials, or collectors with raised medians	Total	13.4	0.866	NV (24)
				PDO	10.1	0.899	
				Fatal/Injury	8.5	0.915	
				Rear-end	4.4	0.956	
				Angle	12.2	0.878	
			Principal arterials, minor arterials, or collectors with TWLTLs	Total	12.6	0.874	
				PDO	13.2	0.868	
				Fatal/Injury	3.8	0.962	
				Rear-end	10.9	0.891	
				Angle	11.8	0.882	
Access Management	Reduce driveway density by 20 driveways per mile[1]	Urban	Principal arterials, minor arterials, or collectors with raised medians	Total	17.5	0.825	NV (24)
				PDO	13.2	0.868	
				Fatal/Injury	11.1	0.889	
				Rear-end	5.8	0.942	
				Angle	16.0	0.840	
			Principal arterials, minor	Total	16.5	0.835	
				PDO	17.1	0.829	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
			arterials, or collectors with TWLTLs	Fatal/Injury	5.1	0.949	
				Rear-end	14.3	0.857	
				Angle	15.5	0.845	
Alignment	Flatten crest of curve	Rural	Arterials, collectors	Total	19.6	0.804	OH (19)
				Fatal/Injury	51.2	0.488	
Alignment	Reduce the average grade rate by 1%[1]	Rural	Two-lane roads	PDO	2.0	0.980	IN (42)
				Fatal/Injury	1.9	0.981	
Alignment	Reduce the average grade rate by 2%[1]	Rural	Two-lane roads	PDO	4.0	0.960	IN (42)
				Fatal/Injury	3.8	0.962	
Alignment	Reduce the average grade rate by 3%[1]	Rural	Two-lane roads	PDO	6.0	0.940	IN (42)
				Fatal/Injury	5.7	0.943	
Alignment	Reduce the average grade rate by 4%[1]	Rural	Two-lane roads	PDO	7.9	0.921	IN (42)
				Fatal/Injury	7.5	0.925	
Alignment	Reduce the average grade rate by 5%[1]	Rural	Two-lane roads	PDO	9.7	0.903	IN (42)
				Fatal/Injury	9.3	0.907	
Alignment	Reduce the average degree of curve by 1 degree[1]	Rural	Two-lane roads	PDO	1.9	0.981	IN (42)
				Fatal/Injury	2.9	0.971	
Alignment	Reduce the average degree of curve by 2 degrees[1]	Rural	Two-lane roads	PDO	3.8	0.962	IN (42)
				Fatal/Injury	5.7	0.943	
Alignment	Reduce the average degree of curve by 3 degrees[1]	Rural	Two-lane roads	PDO	5.7	0.943	IN (42)
				Fatal/Injury	8.4	0.916	
Alignment	Reduce the average degree of curve by 4 degrees[1]	Rural	Two-lane roads	PDO	7.5	0.925	IN (42)
				Fatal/Injury	11.1	0.889	
Alignment	Reduce the average degree of curve by 5 degrees[1]	Rural	Two-lane roads	PDO	9.3	0.907	IN (42)
				Fatal/Injury	13.6	0.864	
Highway Lighting	Install lighting on a roadway segment	Urban and rural	Not specified	Nighttime	20.0	0.80	Not specified (17)
				Nighttime Fatal/Injury	29.0	0.71	
Highway Lighting	Install lighting at a signalized intersection	Urban	Not specified	Daytime	-3.0	1.03	MN (6)
				Nighttime	3.0	0.97	
		Rural	Not specified	Daytime	2.0	0.98	
				Nighttime	2.0	0.98	
		Urban	Not specified	Daytime	-5.0	1.05	MN (6)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Highway Lighting	Install lighting at a stop-controlled intersection			Nighttime	9.0	0.91	
		Rural	Not specified	Daytime	-9.0	1.09	
				Nighttime	-7.0	1.07	
Highway Lighting	Install lighting at an interchange	Urban and rural	Arterials, collectors	Total	50.4	0.496	OH (19)
				Fatal/Injury	26.0	0.74	
Intersection Geometry	Add a left-turn lane on one major approach to a signalized intersection	Urban	Three-leg intersections	Total	7.0	0.930	IA, IL, LA, MN, NE, NC, OR, VA (18)
			Four-leg intersections	Total	10.0	0.900	
		Rural	Three-leg intersections	Total	15.0	0.850	
			Four-leg intersections	Total	18.0	0.820	
Intersection Geometry	Add a left-turn lane on one major approach to an unsignalized intersection	Urban	Three-leg intersections	Total	33.0	0.670	IA, IL, LA, MN, NE, NC, OR, VA (18)
			Four-leg intersections	Total	27.0	0.730	
		Rural	Three-leg intersections	Total	44.0	0.560	
			Four-leg intersections	Total	28.0	0.720	
Intersection Geometry	Add a right-turn lane on one major approach to a signalized intersection	Urban	Four-leg intersections	Total	4.0	0.960	IA, IL, LA, MN, NE, NC, OR, VA (18)
Intersection Geometry	Add a right-turn lane on one major approach to an unsignalized intersection	Rural	Four-leg intersections	Total	14.0	0.860	IA, IL, LA, MN, NE, NC, OR, VA (18)
Intersection Geometry	Convert diamond interchange to diverging diamond interchange (DDI)	Urban	Principal arterial, other freeways and expressways	Total	33	0.67	KY, MO, NY, TN (20)
				Injury	41	0.59	
				Angle	67	0.33	
				Rear-end	36	0.64	
				Sideswipe	-27	1.27	
				Single-vehicle	24	0.76	
Intersection Geometry	Convert intersection on low-speed road to a roundabout	Urban and rural	Intersections where all approaches are low-speed (less than 45 mph)	Total	-9.9	1.099	WI (31)
				Fatal/Injury	52.7	0.473	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Intersection Geometry	Convert intersection on high-speed road to a roundabout	Urban and rural	Intersections where at least one approach is high-speed (45 mph or greater)	Total	34.1	0.659	WI (31)
				Fatal/Injury	49.4	0.506	
Intersection Geometry	Convert intersection to a single-lane roundabout	Urban and rural	Intersections with low- and high-speed approaches	Total	36.0	0.640	WI (31)
				Fatal/Injury	18.2	0.818	
Intersection Geometry	Convert intersection to a multilane roundabout	Urban and rural	Intersections with low- and high-speed approaches	Total	-6.2	1.062	WI (31)
				Fatal/Injury	63.3	0.367	
Intersection Geometry	Convert two-way stop-controlled intersection to a roundabout	Urban	Intersections on two- or four-lane roads	Total	27.0	0.73	CA, CO, CT, FL, KS, MD, ME, MI, MO, MS, NV, OR, SC, UT, VT, WA WI (31, 33)
				Fatal/Injury	58.1	0.419	
		Rural	Intersections on two- or four-lane roads	Total	48.2	0.518	
				Fatal/Injury	61.2	0.388	
Intersection Geometry	Convert all-way stop-controlled intersection to a roundabout	Urban and rural	Intersections on two- or four-lane roads	Total	-7.4	1.074	CA, CO, CT, FL, KS, MD, ME, MI, MO, MS, NV, OR, SC, UT, VT, WA WI (31, 33)
				Fatal/Injury	8.7	0.913	
Intersection Geometry	Convert signalized intersection to a roundabout	Urban	Intersections on two- or four-lane roads	Total	12.4	0.876	CA, CO, CT, FL, IN, KS, MD, ME, MI, MO, MS, NC, NV, NY, OR, SC, UT, VT, WA, WI (15, 31, 33)
				Fatal/Injury	66.1	0.339	
		Rural	Intersections on two- or four-lane roads	Total	26.2	0.738	
				Fatal/Injury	71.5	0.285	
Intersection Geometry	Convert a non-controlled or yield-controlled intersection to a roundabout	Urban and rural	Intersections on two- or four-lane roads	Total	-24.2	1.242	WI (31)
				Fatal/Injury	100.0	0	
Intersection Geometry	Convert two-way stop-controlled intersection to J-turn intersection	Rural	Intersections of four-lane divided, high-speed roads and minor roads	Total	34.8	0.652	MO (8)
				Fatal/Injury	53.7	0.463	
Intersection Geometry		Urban and rural	Four-leg intersections	Total	33.8	0.662	WI (30)
				Fatal/Injury	35.6	0.644	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
	Improve left-turn lane offset to create positive offset			Left-turn	38.0	0.62	
				Rear-end	31.7	0.683	
Intersection Geometry	Improve intersection sight distance	Urban and rural	Not specified	Total	33.0	0.67	Based on AK, AZ, CA, IA, KY, MO (13)
				Right-angle	21.0	0.79	Based on AZ, MO, MN (13)
				Left-turn	13.0	0.87	Based on AZ, MO (13)
				Sideswipe	43.0	0.57	Based on AK, MO (13)
Intersection Traffic Control	Change left-turn phasing on one approach from permitted to protected/permitted phasing	Urban	Four-leg intersections	Total	-8.1	1.081	NC, Toronto (39)
				Fatal/Injury	0.5	0.995	
				Left-turn	7.5	0.925	
				Rear-end	-9.4	1.094	
Intersection Traffic Control	Change left-turn phasing on more than one approach from permitted to protected/permitted phasing	Urban	Four-leg intersections	Total	4.2	0.958	NC, Toronto (39)
				Fatal/Injury	8.6	0.914	
				Left-turn	21.3	0.787	
				Rear-end	-5.0	1.050	
Intersection Traffic Control	Change left-turn phasing from permitted or permitted/protected to protected-only phasing	Urban	Signalized intersections	Total	1	0.99	NC (17)
				Left-turn	99	0.01	
Intersection Traffic Control	Supplement left-turn phasing from at least one permitted approach with flashing yellow arrow	Urban	Four-leg intersections	Total	24.7	0.753	NC, OR, WA (39)
				Left-turn	36.5	0.635	
Intersection Traffic Control	Change left-turn phasing from protected/permitted to flashing yellow arrow	Urban	Four-leg intersections	Total	7.8	0.922	NC, OR, WA (39)
				Left-turn	19.4	0.806	
Intersection Traffic Control	Change left-turn phasing from protected to flashing yellow arrow	Urban	Four-leg intersections	Total	-33.8	1.338	NC, OR, WA (39)
				Left-turn	-124.2	2.242	
Intersection Traffic Control	Convert two-way stop control to all-way stop control	Urban and rural	Four-leg intersections	Total	68	0.32	NC (34)
				Fatal/Injury	77	0.23	
				Frontal impact	75	0.25	
				Ran stop sign	15	0.85	
	Improve signal visibility	Urban		Daytime PDO	9.9	0.901	British Columbia (9)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Intersection Traffic Control			Four-leg intersections on three- to four-lane roads	Daytime Fatal/Injury	-0.4	1.004	
				Nighttime PDO	13.3	0.867	
				Nighttime Fatal/Injury	9.8	0.902	
Intersection Traffic Control	Increase yellow change interval (1.0 seconds)	Urban	Three- and four-leg intersections	Total	-14.1	1.141	CA, MD (39)
				Fatal/Injury	-7.3	1.073	
				Rear-end	6.6	0.934	
				Angle	-7.6	1.076	
Intersection Traffic Control	Increase all-red clearance interval (average of 1.1 seconds)	Urban	Three- and four-leg intersections	Total	20.2	0.798	CA, MD (39)
				Fatal/Injury	13.7	0.863	
				Rear-end	19.6	0.804	
				Angle	3.4	0.966	
Intersection Traffic Control	Increase yellow interval (average of 0.8 seconds) and add all-red interval (average of 1.2 seconds)	Urban	Three- and four-leg intersections	Total Fatal/Injury	1.0 -2.0	0.990 1.020	CA, MD (39)
				Rear-end	-11.7	1.117	
				Angle	3.9	0.961	
Intersection Traffic Control	Install transverse rumble strips on approaches to stop-controlled intersection	Rural	Three-leg intersections on major collectors	Total	-22.3	1.223	IA, MN (38)
				PDO	-28.4	1.284	
				Fatal/Incap. Inj.	59	0.41	
			Four-leg intersections on major collectors	Total	-6.6	1.066	
				PDO	-13.8	1.138	
				Fatal/Incap. Inj.	34.8	0.652	
Intersection Traffic Control	Install new traffic signal at previously stop-controlled intersection	Urban	Three-leg intersections	Fatal/Injury	14	0.86	CA, FL, MD, VA, WI, Toronto (25)
				Right-angle Fatal/Injury	34	0.66	
				Rear-end Fatal/Injury	-50	1.5	
			Four-leg intersections	Fatal/Injury	23	0.77	
				Right-angle Fatal/Injury	67	0.33	
				Rear-end Fatal/Injury	-38	1.38	
		Rural	Three- and four-leg intersections	Total	44	0.56	CA, MN (17)
				Right-angle	77	0.23	
				Rear-end	-58	1.58	
				Left-turn	60	0.40	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Intersection Traffic Control	Replace standard stop sign with flashing LED stop sign	Urban and rural	Two-lane highways	Right-angle	41.5	0.585	MN (7)
Intersection Traffic Control	Retime signal change intervals to Institute of Transportation Engineers (ITE) standards	Urban	Four-leg intersections	Total	8	0.92	NY (32)
				Fatal/Injury	12	0.88	
				Rear-end	-12	1.12	
				Rear-end Fatal/Injury	-8	1.08	
				Angle	4	0.96	
				Angle Fatal/Injury	-6	1.06	
				Vehicle/bicycle and vehicle/pedestrian	37	0.63	
				Vehicle/bicycle and vehicle/pedestrian Fatal/Injury	37	0.63	
Intersection Lighting	Install lighting	Urban and rural	Four-leg intersections	Total	10	0.90	IN (48)
			Three-leg interactions	Total	16	0.84	
ITS And Advanced Technology	Install actuated advance intersection warning system at high-speed intersection	Urban and rural	Four-lane high-speed divided highways (major road)	Total	8.2	0.918	NE (2)
				Fatal/Injury	11.3	0.887	
				Rear-end	1.2	0.988	
				Right-angle	43.6	0.564	
ITS And Advanced Technology	Install changeable horizontal curve speed warning signs	Rural	Two-lane highways	Total	5.0	0.95	AZ, FL, IA, OH, OR, TX, WA (16)
ITS And Advanced Technology	Install variable speed limit signs	Urban	Principal arterial interstates	Total	8.0	0.92	MO (5)
ITS And Advanced Technology	Install "Vehicle Entering When Flashing" (VEWF) system with advance post mounted signs on major	Urban and rural	Highways with 35-55 mph mainline approach speeds	Total	32	0.68	NC (35)
				Fatal/Injury	27	0.73	
				Target (angle, head-on, left-	32	0.68	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
	approach and loops on minor approach			turn, and right-turn)			
Pavement	Improve pavement condition from poor (critical condition index below 60) to good (critical condition index above 70)	Rural	Two-lane highways	Total	-3.0	1.03	VA (46)
				Fatal/Injury	26.0	0.74	
Pedestrians	Construct pedestrian bridge or tunnel	Urban	Not specified	Pedestrian	86	0.14	Based on AK, AZ, KY, MO (13)
Pedestrians	Install High intensity Activated crossWalK (HAWK) at intersection	Urban	Crossings of four- to six-lane roads	Total	29	0.71	AZ (12)
				Fatal/Incap. Inj.	15	0.85	
				Pedestrian	69	0.31	
Pedestrians	Install sidewalk	Urban	Not specified	Pedestrian	74	0.26	Based on AK, AZ, KY, MO, OK (13)
Railroads	Build grade-separated crossing	Urban and rural	Not specified	Total	39	0.61	Based on IA (13)
Railroads	Eliminate railroad crossing	Urban and rural	Not specified	Total	75	0.25	Based on IA (13)
Railroads	Install gates at crossings with signs	Urban and rural	Arterials, collectors, local roads	Total	93	0.07	Canada (26)
Railroads	Upgrade signs to flashing lights	Urban and rural	Arterials, collectors, local roads	Total	77	0.23	Canada (26)
Roadside	Increase median width from 10 feet to 20 feet	Rural	Four-lane divided highways	Multiple vehicle	9	0.91	CA, KY, MN (40)
Roadside	Increase median width from 10 feet to 30 feet	Rural	Four-lane divided highways	Multiple vehicle	17	0.83	CA, KY, MN (40)
Roadside	Increase median width from 10 feet to 40 feet	Rural	Four-lane divided highways	Multiple vehicle	25	0.75	CA, KY, MN (40)
Roadside	Increase median width from 10 feet to 50 feet	Rural	Four-lane divided highways	Multiple vehicle	32	0.68	CA, KY, MN (40)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Roadside	Increase median width from 10 feet to 60 feet	Rural	Four-lane divided highways	Multiple vehicle	38	0.62	CA, KY, MN (40)
Roadside	Increase median width from 10 feet to 70 feet	Rural	Four-lane divided highways	Multiple vehicle	43	0.57	CA, KY, MN (40)
Roadside	Increase median width from 10 feet to 80 feet	Rural	Four-lane divided highways	Multiple vehicle	49	0.51	CA, KY, MN (40)
Roadside	Install guardrail	Urban and rural	Not specified	Total	11	0.890	Based on AZ, IA, IN, KY, MO (13)
				Non-incapac. /Possible	40	0.600	
				Incap./Fatal	65	0.350	
				Run-off-the-road	30	0.700	
Roadside	Install cable median barrier (high-tensioned) on depressed median of 50 feet wide or wider	Rural	Principal arterial interstates	Multiple-vehicle, opposite direction (cross median, frontal and opposing direction sideswipe, head-on)	96	0.04	IN (45)
				Single-vehicle crashes (fixed object, run-off-the-road)	-72	1.72	
Roadside	Install concrete median barrier	Rural	Interstates	Single-vehicle	-120	2.2	CO, IL, IN, MO, NY, OH, OR, WA (41)
				Multiple-vehicle, same direction	20	0.8	
				Multiple-vehicle opposite direction	100	0	
Roadside	Change in sideslope from 1V:3H to 1V:4H	Rural	Not specified	PDO	29	0.71	Not specified (10)
				Fatal/Injury	42	0.58	
Roadside		Rural	Not specified	PDO	24	0.76	Not specified (10)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
	Change in sideslope from 1V:4H to 1V:6H			Fatal/Injury	22	0.78	
Roadside	Remove or relocate fixed objects outside of clear zone	Urban and rural	Arterials, collectors	Total	38.2	0.618	OH (19)
				Fatal/Injury	38.1	0.619	
Road Diet	Re-stripe four-lane undivided road to three-lane (with TWLTL)	Urban	Minor arterials	Total	29	0.71	CA, IA, WA (17)
Roadway Delineation	Add no passing striping	Rural	Not specified	Total	53	0.47	Based on MT (13)
				Head-on	40	0.60	Based on KY, MO (13)
				Sideswipe	40	0.60	
Roadway Delineation	Install centerline rumble strips	Urban	Two-lane roads	Target (head-on, opposite-direction sideswipe)	40	0.60	CA, CO, DE, MD, MN, OR, PA, WA (43)
				Target Fatal/Injury	64	0.36	
		Rural	Two-lane roads	Total	9	0.91	
				Fatal/Injury	12	0.88	
				Target	30	0.70	
				Target Fatal/Injury	44	0.56	
Roadway Delineation	Install shoulder rumble strips	Rural	Two-lane roads	Run-off-the-road	15	0.85	MN, MO, PA (43)
				Run-off-the-road Fatal/Injury	29	0.71	
			Freeways	Run-off-the-road	11	0.89	
				Run-off-the-road Fatal/Injury	16	0.84	
Roadway Delineation	Install centerline plus shoulder rumble strips	Rural	Two-lane roads	Total	18.6	0.814	KY, MI, MO, PA (21, 23)
				Fatal/Injury	22.9	0.771	
				Head-on	36.8	0.632	
				Run-off-the-road	25.8	0.742	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
				Opposite-direction sideswipe	23.3	0.767	
Roadway Delineation	Install edgeline pavement markings on curves	Rural	Two-lane highways	Total	25.9	0.741	TX (44)
				Run-off-the-road	11.0	0.89	
				Speed-related (nighttime)	3.7	0.963	
Roadway Delineation	Install edgeline pavement markings on tangent sections	Rural	Two-lane highways	Total	6.1	0.939	TX (44)
				Run-off-the-road	13.4	0.866	
				Speed-related (nighttime)	3.4	0.966	
Roadway Delineation	Install raised pavement markers	Rural	Two-lane highways with AADT 0-5000, curve radius R => 1640 ft	Nighttime	-16	1.16	IL, NJ, NY, PA (4)
			Two-lane highways with AADT 5001-15000, curve radius R => 1640 ft	Nighttime	1	0.99	
			Two-lane highways with AADT 15001-20000, curve radius R => 1640 ft	Nighttime	24	0.76	
			Two-lane highways with AADT 0-5000, curve radius R < 1640 ft	Nighttime	-43	1.43	
			Two-lane highways with AADT 5001-	Nighttime	-26	1.26	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
			15000, curve radius R < 1640 ft				
			Two-lane highways with AADT 15001-20000, curve radius R < 1640 ft	Nighttime	-3	1.03	
			Four-lane freeways with AADT <= 20000	Nighttime	-13	1.13	MO, NY, PA, WI (4)
			Four-lane freeways with AADT 20001-60000	Nighttime	6	0.94	
			Four-lane freeways with AADT > 60000	Nighttime	33	0.67	
Segments	Increase in number of through lanes by 1 lane[1]	Urban	Multilane	PDO	61.3	0.387	IN (42)
				Fatal/Injury	66.5	0.335	
Segments	Convert two-lane roadway to four-lane divided roadway	Urban	Before: Two-lane roadway After: Four-lane divided roadway	Total	65.9	0.341	FL (1)
				PDO	64.9	0.351	
				Fatal/Injury	63.3	0.367	
		Rural	Before: Two-lane roadway After: Four-lane divided roadway	Total	28.8	0.712	
				PDO	30.9	0.691	
				Fatal/Injury	45.1	0.549	
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 7 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	10	0.90	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 8 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	62	0.38	PA (14)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 5 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	13	0.87	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 6 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	16	0.84	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 7 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-96	1.96	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 4 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-4	1.04	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 5 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-6	1.06	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 6 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	25	0.75	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 3 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-11	1.11	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 4 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-14	1.14	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 5 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-22	1.22	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 2 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-16	1.16	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 3 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-19	1.19	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 4 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-20	1.20	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 1 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-85	1.85	PA (14)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 2 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-12	1.12	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 3 foot shoulders	Rural	Two-lane highways	Run-off-the-road, head-on, sideswipe	-13	1.13	PA (14)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 0 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-42.7	1.427	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 1 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-34.5	1.345	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 2 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-26.7	1.267	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 3 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-19.4	1.194	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 4 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-12.6	1.126	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 5 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-6.1	1.061	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 7 foot shoulders[1]	Urban	Urban and suburban arterials	Total	5.8	0.942	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 8 foot shoulders[1]	Urban	Urban and suburban arterials	Total	11.2	0.888	IL (22)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 9 foot shoulders[1]	Urban	Urban and suburban arterials	Total	16.3	0.837	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 12 foot lanes and 10 foot shoulders[1]	Urban	Urban and suburban arterials	Total	21.1	0.789	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 0 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-270.5	3.705	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 1 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-248.4	3.484	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 2 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-227.6	3.276	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 3 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-208	3.08	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 4 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-189.6	2.896	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 5 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-172.3	2.723	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 6 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-156	2.56	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot	Urban	Urban and suburban arterials	Total	-140.7	2.407	IL (22)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
	lanes and 7 foot shoulders[1]						
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 8 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-126.3	2.263	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 9 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-112.8	2.128	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 10 foot lanes and 10 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-100.1	2.001	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 0 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-14.2	1.142	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 1 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-10.4	1.104	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 2 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-6.8	1.068	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 3 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-3.3	1.033	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 4 foot shoulders[1]	Urban	Urban and suburban arterials	Total	0.1	0.999	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 5 foot shoulders[1]	Urban	Urban and suburban arterials	Total	3.4	0.966	IL (22)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 6 foot shoulders[1]	Urban	Urban and suburban arterials	Total	6.6	0.934	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 7 foot shoulders[1]	Urban	Urban and suburban arterials	Total	9.7	0.903	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 8 foot shoulders[1]	Urban	Urban and suburban arterials	Total	12.6	0.874	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 9 foot shoulders[1]	Urban	Urban and suburban arterials	Total	15.5	0.845	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 11 foot lanes and 10 foot shoulders[1]	Urban	Urban and suburban arterials	Total	18.3	0.817	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 0 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-23.8	1.238	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 1 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-16.8	1.168	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 2 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-10.1	1.101	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 3 foot shoulders[1]	Urban	Urban and suburban arterials	Total	-3.8	1.038	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot	Urban	Urban and suburban arterials	Total	2.1	0.979	IL (22)

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
	lanes and 4 foot shoulders[1]						
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 5 foot shoulders[1]	Urban	Urban and suburban arterials	Total	7.6	0.924	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 6 foot shoulders[1]	Urban	Urban and suburban arterials	Total	12.9	0.871	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 7 foot shoulders[1]	Urban	Urban and suburban arterials	Total	17.9	0.821	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 8 foot shoulders[1]	Urban	Urban and suburban arterials	Total	22.5	0.775	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 9 foot shoulders[1]	Urban	Urban and suburban arterials	Total	26.9	0.731	IL (22)
Segments	Convert 12 foot lanes and 6 foot shoulders to 13 foot lanes and 10 foot shoulders[1]	Urban	Urban and suburban arterials	Total	31.1	0.689	IL (22)
Segments	Extend on-ramp acceleration lane by 30 meters (about 100 feet)	Urban and rural	Grade-separated junctions	Total	11	0.89	Not specified (10)
Segments	Extend off-ramp deceleration lane by 30 meters (about 100 feet)	Urban and rural	Grade-separated junctions	Total	7	0.93	Not specified (10)
Segments	Install passing relief lane	Rural	Two-lane highways	Total	33	0.67	MI (3)
				Fatal/Injury	29	0.71	
				Target (head-on, rear-end, run-off-the-road, sideswipe)	47	0.53	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
				Peak month (June, July, August)	46	0.54	
				Off-peak month	28	0.72	
Segments	Increase lane width by 1 foot[1]	Urban	Two-lane roads	PDO	6.6	0.934	IN (42)
				Fatal/Injury	14.2	0.858	
			Multilane roads	PDO	2.0	0.980	
				Fatal/Injury	14.1	0.859	
		Rural	Two-lane roads	PDO	8.2	0.918	
				Fatal/Injury	7.4	0.926	
			Multilane roads	PDO	17.7	0.823	
				Fatal/Injury	21.2	0.788	
Segments	Increase lane width by 2 feet[1]	Urban	Two-lane roads	PDO	12.7	0.873	IN (42)
				Fatal/Injury	26.3	0.737	
			Multilane roads	PDO	4.0	0.960	
				Fatal/Injury	26.2	0.738	
		Rural	Two-lane roads	PDO	15.7	0.843	
				Fatal/Injury	14.3	0.857	
			Multilane roads	PDO	32.2	0.678	
				Fatal/Injury	37.9	0.621	
Segments	Increase lane width by 3 feet[1]	Urban	Two-lane roads	PDO	18.4	0.816	IN (42)
				Fatal/Injury	36.8	0.632	
			Multilane roads	PDO	6.0	0.940	
				Fatal/Injury	36.6	0.634	
		Rural	Two-lane roads	PDO	22.6	0.774	
				Fatal/Injury	20.7	0.793	
			Multilane roads	PDO	44.2	0.558	
				Fatal/Injury	51.1	0.489	
Segments	Increase lane width by 4 feet[1]	Urban	Two-lane roads	PDO	23.8	0.762	IN (42)
				Fatal/Injury	45.7	0.543	
			Multilane roads	PDO	7.9	0.921	
				Fatal/Injury	45.6	0.544	
		Rural	Two-lane roads	PDO	28.9	0.711	
				Fatal/Injury	26.6	0.734	
			Multilane roads	PDO	54.0	0.460	
				Fatal/Injury	61.5	0.385	
Shoulder Treatment	Increase right shoulder width by 1 foot[1]	Urban	Two-lane roads	PDO	1.7	0.983	IN (42)
			Multilane roads	PDO	1.6	0.984	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
		Rural	Two-lane roads	PDO	2.3	0.977	
				Fatal/Injury	2.8	0.972	
			Multilane roads	Fatal/Injury	4.0	0.960	
Shoulder Treatment	Increase right shoulder width by 2 feet[1]	Urban	Two-lane roads	PDO	3.5	0.965	IN (42)
			Multilane roads	PDO	3.1	0.969	
		Rural	Two-lane roads	PDO	4.6	0.954	
				Fatal/Injury	5.4	0.946	
			Multilane roads	Fatal/Injury	7.9	0.921	
Shoulder Treatment	Increase right shoulder width by 3 feet[1]	Urban	Two-lane roads	PDO	5.1	0.949	IN (42)
			Multilane roads	PDO	4.7	0.953	
		Rural	Two-lane roads	PDO	6.8	0.932	
				Fatal/Injury	8.0	0.920	
			Multilane roads	Fatal/Injury	11.6	0.884	
Shoulder Treatment	Increase right shoulder width by 4 feet[1]	Urban	Two-lane roads	PDO	6.8	0.932	IN (42)
			Multilane roads	PDO	6.2	0.938	
		Rural	Two-lane roads	PDO	8.9	0.911	
				Fatal/Injury	10.6	0.894	
			Multilane roads	Fatal/Injury	15.2	0.848	
Shoulder Treatment	Increase left/inside shoulder width by 1 foot[1]	Urban	Multilane roads	Fatal/Injury	18.5	0.815	IN (42)
		Rural	Multilane roads	PDO	4.3	0.957	
				Fatal/Injury	6.7	0.933	
Shoulder Treatment	Increase left/inside shoulder width by 2 feet[1]	Urban	Multilane roads	Fatal/Injury	33.6	0.664	IN (42)
		Rural	Multilane roads	PDO	8.5	0.915	
				Fatal/Injury	13.0	0.870	
Shoulder Treatment	Increase left/inside shoulder width by 3 feet[1]	Urban	Multilane roads	Fatal/Injury	45.9	0.541	IN (42)
		Rural	Multilane roads	PDO	12.4	0.876	
				Fatal/Injury	18.9	0.811	
Shoulder Treatment	Increase left/inside shoulder width by 4 feet[1]	Urban	Multilane roads	Fatal/Injury	56.0	0.440	IN (42)
		Rural	Multilane roads	PDO	16.2	0.838	
				Fatal/Injury	24.3	0.757	
Signs	Install chevron signs on horizontal curves	Rural	Two-lane highways	Total	4.3	0.957	WA (37)
				Fatal/Injury	16.4	0.836	
				Lane departure	5.9	0.941	
				Nighttime	24.5	0.755	
				Nighttime lane departure	22.1	0.779	
Signs	Increase retroreflectivity of stop signs	Urban and rural	Three- and four-leg stop-	Total	1.2	0.988	CT, SC (28)
				Fatal/Injury	6.7	0.933	

Category	Countermeasure	Area Type	Facility Type	Crash Type	CRF	CMF	States and (reference number)
			controlled intersections	Right-angle	-1.2	1.012	
				Rear-end	-2.2	1.022	
				Nighttime	4.4	0.956	
				Daytime	-0.1	1.001	
Signs	Install flashing beacons at stop-controlled intersections	Urban	Two-lane highways	Angle	-12	1.12	NC, SC (36)
		Rural	Two-lane highways	Angle	16	0.84	
Speed Management	Lower posted speed by 15–20 mph	Urban and rural	Nonlimited access highways	Total	6	0.94	AZ, CA, CO, CT, DE, ID, IL, IN, ME, MD, MA, MI, MS, NE, NJ, NM, OH, OK, TN, TX, VA, WV (27)
Speed Management	Lower posted speed by 10 mph	Urban and rural	Nonlimited access highways	Total	4	0.96	AZ, CA, CO, CT, DE, ID, IL, IN, ME, MD, MA, MI, MS, NE, NJ, NM, OH, OK, TN, TX, VA, WV (27)
Speed Management	Lower posted speed by 5 mph	Urban and rural	Nonlimited access highways	Total	-17	1.17	AZ, CA, CO, CT, DE, ID, IL, IN, ME, MD, MA, MI, MS, NE, NJ, NM, OH, OK, TN, TX, VA, WV (27)
Speed Management	Raise posted speed by 5 mph	Urban and rural	Nonlimited access highways	Total	8	0.92	AZ, CA, CO, CT, DE, ID, IL, IN, ME, MD, MA, MI, MS, NE, NJ, NM, OH, OK, TN, TX, VA, WV (27)
Speed Management	Raise posted speed by 10–15 mph	Urban and rural	Nonlimited access highways	Total	15	0.85	AZ, CA, CO, CT, DE, ID, IL, IN, ME, MD, MA, MI, MS, NE, NJ, NM, OH, OK, TN, TX, VA, WV (27)
Speed Management	Set appropriate speed limit	Urban and rural	Not specified	Total	28	0.72	Based on KY, MO, MT (13)

[1] CRF/CMF given in the form of a function in the CMF Clearinghouse or in the report/paper. For this table, the CRFs/CMFs have been discretized for various levels of the safety countermeasure. The user is referred to the source (provided by the reference number) for the original functional form.

CRF/CMF Sources

1. Ahmed, M. M., Abdel-Aty, M., & Park, J. (2015). Evaluation of the safety effectiveness of the conversion of two-lane roadways to four-lane divided roadways: Bayesian versus empirical bayes. *Transportation Research Record: Journal of the Transportation Research Board*, *2515*, 41–49.
2. Appiah, J., Naik, B., Wojtal, R., & Rilett, L. R. (2011). Safety Effectiveness of actuated advance warning systems. *Transportation Research Record: Journal of the Transportation Research Board*, *2250*, 19–24.
3. Bagdade, J., Ceifetz, A., Myers, M., Redinger, C., Persaud, B. N., & Lyon, C. A. (2012). *Evaluating performance and making best use of passing relief lanes*. Michigan Department of Transportation.
4. Bahar, G., Mollett, C., Persaud, B., Lyon, C., Smiley, A., Smahel, T., & McGee, H. (2004). *Safety evaluation of permanent raised pavement marker* (NCHRP Report 518). Transportation Research Board.
5. Bham, G. H., Long, S., Baik, H., Ryan, T., Gentry, L., Lall, K., & Schaeffer, B. (2010). *Evaluation of variable speed limits on I-270/I-255 in St. Loui*s. Missouri Department of Transportation.
6. Bullough, J. D., Donnell, E. T., & Rea, M. S. (2013). To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis and Prevention*, *53*, 65–77.
7. Davis, G. A., Hourdos, J., & Xiong, H. (2014). *Estimating the crash reduction and vehicle dynamics effects of flashing LED stop signs*. Minnesota Department of Transportation.
8. Edara, P., Sun, C., & Breslow, S. (2014). *Evaluation of J-turn intersection design performance in Missouri*. Missouri Department of Transportation.
9. El-Basyouny, K., Sayed, T., El Esawey, M., & Pump, J. (2012). Investigating effect of collision aggregation on safety evaluations with models of multivariate linear intervention: Case study of program to upgrade signal heads. *Transportation Research Record: Journal of the Transportation Research Board*, *2280*, 110–117.
10. Elvik, R., & Vaa, T. (2004). *The handbook of road safety* (1st ed.). Oxford: Elsevier.
11. Fitzpatrick, K., Park, E. S., & Schneider IV, W. H. (2008). Potential accident modification factors for driveway density on rural highways: From Texas data. T*ransportation Research Record: Journal of the Transportation Research Board*, *2083*, 49–61.
12. Fitzpatrick, K., & Park, E. S. (2010). *Safety effectiveness of the HAWK pedestrian crossing treatment*. Texas Transportation Institute and Federal Highway Administration.
13. Gan, A., Shen, J., & Rodriguez, A. (2005). *Update of Florida crash reduction factors and countermeasures to improve the development of district safety improvement projects*. Lehman Center for Transportation Research and Florida Department of Transportation Safety Office.
14. Gross, F., Jovanis, P. P., Eccles, K., & Chen, K.-Y. (2009). *Safety evaluation of lane and shoulder width combinations on rural, two-lane, undivided roads*. Federal Highway Administration.
15. Gross, F., Lyon, C., Persaud, B., & Srinivasan, R. (2013). Safety effectiveness of converting signalized intersections to roundabouts. *Accident Analysis and Prevention*, *50*, 234–241.
16. Hallmark, S. L., Hawkins, N., & Smadi, O. (2015). *Evaluation of dynamic speed feedback signs on curves: A national demonstration project*. Iowa State University and Federal Highway Administration.

17. Harkey, D., Srinivasan, R., Baek, J., Council, F., Eccles, K., Lefler, N., & Bonneson, J. (2008). *Accident modification factors for traffic engineering and ITS improvements* (NCHRP Report 617). Transportation Research Board.
18. Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Kohlman Rabbani, E. R., Hauer, E., Elefteriadou, L., & Griffith M. S. (2003). Safety effectiveness of intersection left- and right-turn lanes. *Transportation Research Record: Journal of the Transportation Research Board*, *1840*, 131–139.
19. Hovey, P., & Chowdhury, M. (2005). *Development of crash reduction factors.* University of Dayton and Ohio Department of Transportation.
20. Hummer, J. E., Cunningham, C. M., Srinivasan, R., Warchol, S., Claros, B., Edara, P., & Sun, C. (2016). Safety evaluation of seven of the earliest diverging diamond interchanges installed in the United States. *Transportation Research Record: Journal of the Transportation Research Board*, *2583*, 25–33.
21. Kay, J., Savolainen, P. T., Gates, T. J., Datta, T. K., Finkelman, J., & Hamadeh, B. (2015). Safety impacts of a statewide centerline rumble strip installation program. *Transportation Research Record: Journal of the Transportation Research Board*, *2515*, 34–40.
22. Le, T. Q., & Porter, R. J. (2013). *Safety effects of cross section design on urban and suburban roads*. Transportation Research Board 92nd Annual Meeting. Washington, D.C.
23. Lyon, C., Persaud, B., & Eccles, K. (2015). *Safety evaluation of centerline plus shoulder rumble strips*. Federal Highway Administration.
24. Mauga, T., & Kaseko, M. (2010). Modeling and evaluating safety impacts of access management features in the Las Vegas, Nevada, Valley. *Transportation Research Record: Journal of the Transportation Research Board*, *2171*, 57–65.
25. McGee, H., Taori, S., & Persaud, B. (2003). *Crash experience warrant for traffic signals* (NCHRP Report 491). Transportation Research Board.
26. Park, Y.-J., & Saccomanno, F. F. (2005). Collision frequency analysis using tree-based stratification. *Transportation Research Record: Journal of the Transportation Research Board*, *1908*, 121–129.
27. Parker Jr., M. R. (1997). *Effects of raising and lowering speed limits on selected roadway sections*. Federal Highway Administration.
28. Persaud, B., Lyon, C., Eccles, K., Lefler, N., & Amjadi, R. (2008a). *Safety evaluation of increasing retroreflectivity of STOP signs*. Federal Highway Administration.
29. Persaud, B., Lyon, C., Eccles, K., Lefler, N., Carter, D., & Amjadi, R. (2008b). *Safety evaluation of installing center two-way left-turn lanes on two-lane roads*. Federal Highway Administration.
30. Persaud, B., Lyon, C., Eccles, K., Lefler, N., & Gross, F. (2009). *Safety Evaluation of offset improvements for left-turn lanes*. Federal Highway Administration.
31. Qin, X., Bill, A., Chitturi, M., & Noyce, D. A. (2013). *Evaluation of roundabout safety*. Transportation Research Board 92nd Annual Meeting, Washington, D.C.
32. Retting, R. A., Chapline, J. F., & Williams, A. F. (2002). Changes in crash risk following re-timing of traffic signal change intervals. *Accident Analysis and Prevention*, *34*(2), 215–220.
33. Rodegerdts, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., & Carter, D. (2007). *Roundabouts in the United States* (NCHRP Report 572). Transportation Research Board.

34. Simpson, C. L., & Hummer, J. E. (2010). Evaluation of the conversion from two-way stop sign control to all-way stop sign control at 53 locations in North Carolina. *Journal of Transportation Safety & Security*, *2*, 239–260.
35. Simpson, C. L., & Troy, S. A. (2013). Safety effectiveness of "vehicle entering when flashing" signs: Evaluation of 74 Stop-controlled intersections in North Carolina. *Transportation Research Record: Journal of the Transportation Research Board*, *2384*, 1–9.
36. Srinivasan, R., Carter, D., Eccles, K., Persaud, B., Lefler, N., Lyon, C., & Amjadi, R. (2008). Safety Evaluation of Flashing Beacons at STOP-Controlled Intersections. Federal Highway Administration.
37. Srinivasan, R., Baek, J., Carter, D., Persaud, B., Lyon, C., Eccles, K., & Lefler, N. (2009). *Safety evaluation of improved curve delineation*. Federal Highway Administration.
38. Srinivasan, R., Baek, J., & Council, F. (2010). Safety Evaluation of Transverse Rumble Strips on Approaches to Stop-Controlled Intersections in Rural Areas. Journal of Transportation Safety & Security, 2(3), 261–278.
39. Srinivasan, R., Baek, J., Smith, S., Sundstrom, C., Carter, D., Lyon, C., & Lefler, N. (2011). *Evaluation of safety strategies at signalized intersections* (NCHRP Report 705). Transportation Research Board.
40. Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., & Lord, D. (2009). *Impact of shoulder width and median width on safety* (NCHRP Report 633). Transportation Research Board.
41. Tarko, A. P., Villwock, N. M., & Blond, N. (2008). Effect of median design on rural freeway safety: Flush medians with concrete barriers and depressed medians. *Transportation Research Record: Journal of the Transportation Research Board*, *2060*, 29–37.
42. Tarko, A. P., Dey, A., & Romero, M. A. (2015). Performance Measure that Indicates Geometry Sufficiency of State Highways. West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.
43. Torbic, D. J., Hutton, J. M., Bokenkroger, C. D., Bauer, K. M., Harwood, D. W., Gilmore, D. K., Dunn, J. M., Ronchetto, J. J., Donnell, E. T., Sommer, III, Garvey, P., Persaud, B., & Lyon, C. (2009). *Guidance for the design and application of shoulder and centerline rumble strips* (NCHRP Report 641). Transportation Research Board.
44. Tsyganov, A. R., Warrenchuk, N. M., & Machemehl, R. B. (2009). *Driver performance and safety effects of edge lines on rural two-lane highways*. Transportation Research Board 88th Annual Meeting, Washington, D.C.
45. Villwock, N., Blond, N., & Tarko, A. P. (2009). *Safety impact of cable barriers on rural interstates*. Transportation Research Board 88th Annual Meeting, Washington, D.C.
46. Zeng, H., Fontaine, M. D., & Smith, B. L. (2014). Estimation of the safety effect of pavement condition on rural, two-lane highways. *Transportation Research Record: Journal of the Transportation Research Board*, *2435*, 45–52.
47. Tarko, A. P., Romero, M., Hall, T., & Sultana, A. (2018). *Updating the crash modification factors and calibrating the IHSDM for Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/03). West Lafayette, IN: Purdue University.
48. Zhao, G., Li, S., & Jiang, Y. (2016). *Safety and cost performance of intersection lightin*g (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/17). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316340

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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