CMF CRASH MODIFICATION FACTORS IN PRACTICE

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Using CMFs to Quantify Safety in the Development and Analysis of Alternatives

The Crash Modification Factors (CMFs) in Practice: Using CMFs to Quantify Safety in the Development and Analysis of Alternatives guide describes and illustrates several opportunities to incorporate the latest methods to quantify safety in the development and analysis of design alternatives using CMFs. The target audience includes planners, engineers, and program managers responsible for the development, review, and evaluation of alternatives. The purpose of this guide is to help raise awareness of opportunities to consider and quantify safety in the development and analysis of alternatives, with a specific focus on the application of CMFs to support this process. The objectives are to 1) identify opportunities to consider safety in the various steps of the design process, 2) describe various methods available for quantifying safety using CMFs, and 3) explain when it would be appropriate to employ each method. By providing safety awareness, practitioners will be better prepared to assess the safety impacts of design alternatives and explicitly consider those impacts during the development and analysis of alternatives.

INTRODUCTION

Historically, it has been very challenging to quantify safety explicitly along with other factors such as operational and environmental impacts during the project development process. Instead, safety has been assumed to be inherent in design policies and practices.

Methods and related tools have been available for several years to quantify the operational and environmental impacts of design decisions. Recently, similar methods and tools have been developed to quantify the safety impacts of these decisions, but these resources are relatively new. There is a need to raise awareness of the current level of road safety knowledge and the methods available to quantify safety in the development and analysis of alternatives. Quantifying safety will help decision-makers better understand the safety impacts of design alternatives and allow safety impacts to be considered in conjunction with other factors. It is important for professionals involved in the development and analysis of alternatives to understand the importance of quantifying safety and using appropriate methods to do so.

Development and analysis of alternatives ensures that multiple options are explored to achieve the goals and objectives of a project. Alternatives development identifies various options for improvement strategies or design elements. Alternatives analysis compares the various designs on a number of factors including safety, cost, operational performance, and environmental and economic impacts. As such, alternatives development and analysis provides an added opportunity to consider safety early in the project development process.

Crash modification factors (CMFs) support a number of safety-related activities in the project development process. The CMFs in Practice series includes five separate guides that identify opportunities to consider and quantify safety in specific activities, including roadway safety management processes, road safety audits, design decisions and exceptions, development and analysis of alternatives, and value engineering. The purpose of the CMFs in Practice series is to help raise awareness of safety, demonstrate the use of CMFs, and introduce other methods to quantify safety in these five activities.

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Safety is explicitly considered in the evaluation of alternatives, but has traditionally been more of a qualitative and nonmonetary consideration. Recently developed methods may allow the project team to quantify the safety performance (i.e., estimate crash frequency) for various alternatives. Estimated crashes can then be converted to a monetary value by applying average crash costs. In this way, safety can be considered in conjunction with other monetary costs during the decision-making process.

Read more for an overview of quantifying safety in the development and analysis of alternatives using crash modification factors (CMFs) or skip to the section that describes available methods for quantifying safety using CMFs. A decision-support chart is provided to help identify when CMF-related methods may be appropriate in the development and analysis of alternatives. Examples are provided to illustrate how these methods can be applied and case studies illustrate how these methods have been applied in particular states in the development and analysis of alternatives. Finally, actual and potential challenges are presented with opportunities to overcome common application issues. While several examples are provided to demonstrate the basic application of CMF-related methods, the State Highway Safety Engineer (or equivalent) or Federal Highway Administration (FHWA) Division Office can provide further guidance and assistance with the application of these methods and the interpretation of results.

Contact information for the FHWA field offices is available at: http://www.fhwa.dot.gov/about/field.cfm.

OVERVIEW OF SAFETY IN THE DEVELOPMENT AND ANALYSIS OF ALTERNATIVES

The development and analysis of alternatives is a fundamental part of the transportation planning process. The transportation planning process begins with the creation of a vision aimed at promoting prosperity, social equity, and environmental quality *(1)*. Vision statements express the desired direction for a transportation system but generally lack specific information. Once a vision has been established, goals and objectives are formulated to define the specific purposes of the transportation planning process. Goals and objectives, in turn, help to identify aspects of the transportation system that are deemed to be of greatest importance, which lead to the selection of system performance measures *(1)*. System performance measures determine what data are to be collected and what analyses are to be performed. The development and analysis of alternatives fits into the transportation planning process at this point. This process typically consists of two steps:

1. Identification of alternatives.
2. Evaluation of alternatives.

First, alternative improvement strategies or projects are identified that address the established goals and objectives. Alternatives are then evaluated to determine which plans are "feasible" and should be recommended for implementation. A brief summary of each step is presented below, noting the steps where safety considerations and analysis can be incorporated. By incorporating safety analysis in the process, agencies can quantify and better understand the anticipated safety performance of alternatives. This is particularly useful for risk management and defending against potential litigation. For example, a project team may consider several alternatives for a given project and select the combination that achieves a reasonable balance between cost, safety, operations, and environmental impacts.

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Identification of Alternatives

The initial identification of alternatives considers all possible courses of action including the "as-is" or "no-build" scenario. The next step is to screen the inclusive list of potential alternatives according to suitable criteria. One possible set of criteria are appropriateness, adequacy, and implementation feasibility *(2)*.

- Appropriateness – assesses whether the course of action addresses the specific goals and objectives set forth in the planning process.
- Adequacy – assesses whether the magnitude of the improvement caused by the course of action would be sufficient to meet the performance expectations.
- Feasibility – assesses whether the course of action can be implemented, given the available resources.

Alternatives that pass the screening process represent "feasible" alternatives. Enough alternatives should be generated to identify tradeoffs among performance goals *(2)*. However, the number of alternatives generated should not be so great that evaluations become unmanageable *(2)*.

Evaluation of Alternatives

The evaluation of alternatives requires the estimation of costs and implications of improvement projects on the performance of a roadway where safety, operations, and other factors are used as performance measures. Once the monetary and nonmonetary impacts have been determined, alternatives are evaluated by comparing their respective costs, impacts, and cost-effectiveness to identify the alternative that achieves the desired balance among these factors.

Safety is typically considered during the development and analysis of alternatives, but has traditionally been assessed based on the compliance of the design to applicable design standards. It was difficult to quantify the safety impacts of alternatives and include with other nonmonetary considerations such as operational, environmental, economic, and accessibility impacts. Agency and user costs have traditionally been considered as the only monetary costs. Agency costs for a given alternative may include construction costs, rehabilitation and maintenance costs, and operating costs.

The evaluation phase is the primary opportunity to use CMFs and related methods to quantify safety impacts in the analysis of alternatives. The application of these methods may allow the project team to estimate the safety performance as they identify and discuss advantages and disadvantages of each alternative. It is possible to convert the estimated safety performance to monetary terms and use economic efficiency criteria, such as a benefit-cost ratio, to evaluate the alternatives. Otherwise, a multi-criteria evaluation is necessary in which monetary and nonmonetary criteria are weighted, scaled, and combined to derive an objective function *(2)*; the alternative with the highest value on the objective function represents the best option.

Design exceptions may arise during the evaluation of alternatives. A design exception is "a documented decision to design a highway element or a segment of highway to design criteria that do not meet minimum values or ranges established for that highway or project" *(3)*. Readers can refer

The estimated safety performance, along with other factors, can help guide decisions in the selection of a reasonable alternative. Safety is only one factor to consider in the project development process and other factors such as operational efficiency, cost-effectiveness, and environmental impacts may take priority in certain cases.

to the companion guide, *CMFs in Practice: Quantifying Safety in Design Decisions and Exceptions (4)* for further guidance on the application of CMFs and related methods to quantify the safety impacts of design decisions and exceptions.

METHODS FOR QUANTIFYING SAFETY IMPACTS IN THE DEVELOPMENT AND ANALYSIS OF ALTERNATIVES

There are several opportunities to identify and address safety impacts in the development and analysis of alternatives. This section focuses on the evaluation of alternatives and identifies several methods and related tools that can be used to compare the safety impacts of alternatives. Safety impacts are quantified by estimating the extent to which each alternative or given set of conditions is likely to impact the frequency and severity of crashes. The safety impacts can then be compared among the alternatives and considered in conjunction with other factors such as operational and environmental impacts and overall project cost.

The safety impacts can be estimated using a number of methods which incorporate one or more of the following inputs: crash modification factors, safety performance functions, observed crash frequency, predicted crash frequency, and expected crash frequency. Engineering judgment is an essential component of each method. These terms are defined below, followed by a discussion of each method. The methods are presented in order of increasing reliability, with a discussion of their strengths and limitations. While the most reliable method is preferred, the most appropriate method depends on the complexity of the decision at hand and the availability of required inputs. Related tools are then identified and can be used to help implement the methods. This section concludes with guidance on how to select an appropriate method based on the decision at hand and availability of required inputs.

Note that while there are several methods available to consider and quantify safety in the development and analysis of alternatives, there is a clear order of preference based on the availability of data and reliability of the methods. Engineering judgment is an essential component of each method.

Inputs

The required inputs are defined below, followed by a discussion of the various methods. More rigorous methods can be employed when more inputs are available; the most rigorous method requires all of the following inputs.

Crash Modification Factors

A crash modification factor (CMF) is an index of the expected change in safety performance following a modification in traffic control strategy or design element. When applied correctly, CMFs can be used to estimate the safety effectiveness of a given strategy, compare the relative safety effectiveness of multiple strategies, and adjust the crash frequency estimated from observed, predicted, or expected crashes. Readers can refer to the *Introduction to Crash Modification Factors* for more information on CMFs and how they are applied *(5)*.

Safety Performance Functions

A safety performance function (SPF) is an equation used to predict the average number of crashes per year at a location as a function of traffic volume and, in some cases, roadway or intersection characteristics (e.g., number of lanes, traffic control, or median type). SPFs are developed for specific facility types based on data from a group of similar sites and the results apply to a set of specified baseline conditions. The results from an SPF can be multiplied by an applicable CMF to account for differences between the actual site conditions and the specified baseline conditions. If an SPF is developed using data from another jurisdiction or time period, then it may be necessary to adjust the SPF through calibration to better reflect local conditions or a different study period. Readers can refer to the *Introduction to Safety Performance Functions (6)* for more information on SPFs and how they are applied.

Observed Crashes

Observed crashes are those reported at a site of interest. For example, there were 15 crashes reported over a three-year period at an urban, stop-controlled intersection. One might estimate that, on average, there will be five crashes per year at this location based on the observed crash history. Using the observed crashes to estimate annual average future crashes assumes that the past performance is a good approximation of the future (e.g., no changes in traffic volume, site conditions, driver behavior, weather, etc).

Predicted Crashes

Predicted crashes are estimated from an SPF. The predicted number of crashes for a given site is an estimate of the average number of crashes per year based on the crash experience at other locations with similar characteristics (e.g., area type, geometry, and operations). One might use the predicted crashes to estimate the future safety performance of a site when the observed crash history is not a good approximation of future conditions (e.g., conditions change over time such as traffic volume, site conditions, driver behavior, weather, etc).

Expected Crashes

Expected crashes are estimated using the Empirical Bayes method, which is a weighted average of the observed and predicted crashes for a site of interest. One might use the expected crashes to estimate future safety performance when there is value in both the observed and predicted crashes for a site of interest. One benefit of using the expected crashes is that it helps to account for the natural variation in crashes (i.e., regression-to-the-mean).

Engineering Judgment

Engineering judgment refers to decisions made based on an evaluation of available pertinent information and a sound understanding of established engineering principles and practices. Applying sound engineering judgment is necessary when selecting and utilizing all methods for quantifying safety impacts. It is also necessary when interpreting the results of a method and considering the safety impacts of various alternatives in conjunction with other factors such as operational and environmental impacts as well as overall project cost.

Methods for Quantifying Safety Impacts

Several methods are available for quantifying safety impacts in the development and analysis of alternatives. The following is a detailed discussion of each method, required inputs, and associated strengths and limitations. It is important to note that the methods are presented in order of increasing reliability and an appropriate method should be selected based on the complexity of the decision at hand and the availability of required inputs. Further guidance on the selection of an appropriate method is provided after the discussion of methods.

Relative Comparison of CMFs

This method is used to estimate the relative magnitude and direction of potential safety impacts based on the anticipated percent change in crash frequency. It does not provide an estimate of the change in the number of crashes (only the percent change). The required inputs for this method include the following:

- Applicable CMFs.
- Engineering judgment.

When there is a lack of required inputs or expertise to employ more rigorous methods, then it may be necessary to simply compare the relative values of applicable CMFs to estimate the safety impacts of a design alternative. For example, a CMF may be identified for converting a signalized intersection to a roundabout and used to estimate the percent change in crashes when the intersection type is a roundabout compared to a conventional signal. A numerical example is provided later in this document in the *Relative Comparison of Design Alternatives using CMFs* section.

The advantages of this method include the following:
- It is relatively simple to apply.
- It does not require an estimate of crashes without treatment to which the CMF would be applied.

The limitations of this method include the following:
- It requires applicable CMFs.
- It does not provide an estimate of the change in the number of crashes (only the percent change).
- It is difficult to compare multiple alternatives when the applicable CMFs are for different crash types or severities.

Observed Crash Frequency with CMF Adjustment

This method is used to estimate the crash frequency for design alternatives. The results can be used to compare the safety performance of design alternatives or included in a benefit-cost analysis to quantify the benefits. The required inputs for this method include the following:
- Observed crashes.
- Applicable CMF(s).
- Engineering judgment.

When there is a lack of required inputs or expertise to employ more rigorous methods, then it may be necessary to estimate the safety impacts of a design alternative based on observed crashes and CMFs. The observed crashes (e.g., five-year average) for the location of interest are used to estimate the average crash frequency for existing conditions. Appropriate CMFs are then applied to estimate the crash frequency under different design alternatives. Compared to the previous method, the observed crash history is the only additional piece of information required. A numerical example is provided later in this document in the *Estimating the Safety Impacts of Alternative Designs Using Observed Crashes and CMFs* section, comparing the safety effectiveness of a traffic signal and roundabout as alternatives to an existing two-way stop-controlled intersection.

The advantages of this method include the following:
- It is relatively simple to apply.
- It provides an estimate of the change in crash frequency (not just the percent change).
- It can be applied when an SPF is not available for the facility type of interest.

The limitations of this method include the following:
- Applicable crash history and CMF(s) are required.
- It does not properly account for changes in traffic volume.
- It is susceptible to regression-to-the-mean bias (i.e., random variation in crashes over time).

Predicted Crash Frequency

This method is used to estimate the crash frequency for design alternatives. The results can be used to compare the safety performance of design alternatives or to quantify the benefits in a benefit-cost analysis. The required inputs for this method include the following:
- Applicable SPF.
- Engineering judgment.

This method applies to situations where the observed crash history is not available (e.g., new construction) or applicable (e.g., proposed conditions differ drastically from the existing conditions). The predicted crash frequency is computed from an applicable SPF.

The advantages of this method include the following:
- It provides an estimate of the change in crash frequency (not just the percent change).
- It can account for changes in traffic volume over time.
- It can be applied when observed crash history is not available or not applicable for the location of interest.

- It includes data from similar sites to reduce the reliance on crash data for any one site.

The limitations of this method include the following:
- An applicable SPF is required that includes the variables of interest. For example, the SPF would need to include a variable for median type if this was a design feature of interest. It may also be necessary to adjust the SPF through calibration to better reflect local conditions or a different study period.
- It is susceptible to regression-to-the-mean bias (i.e., random variation in crashes over time).

Predicted Crash Frequency with CMF Adjustment

This method is used to estimate the crash frequency for design alternatives. The results can be used to compare the safety performance of design alternatives or to quantify the benefits in a benefit-cost analysis. The required inputs for this method include the following:
- Applicable SPF.
- Applicable CMF(s).
- Engineering judgment.

This method applies to situations where observed crash history is not available (e.g., new construction) or applicable (e.g., proposed conditions differ drastically from the existing conditions) and where the SPF does not include one or more variables of interest. In these cases, an applicable SPF is used to estimate the predicted crashes for a set of baseline conditions and applicable CMFs are applied to estimate the predicted crashes for other conditions of interest. For example, an applicable SPF may be available for the facility type of interest, but not include a variable for median type. The SPF would be used to estimate the predicted crashes for baseline conditions and CMFs would be applied to estimate the impacts of different median types.

The advantages of this method include the following:
- It provides an estimate of the change in crash frequency (not just the percent change).
- It can account for changes in traffic volume over time.
- It can be applied when observed crash history is not available or not applicable for the location of interest.
- It includes data from similar sites to reduce the reliance on crash data for any one site.
- It does not require an SPF that includes all variables of interest.

The limitations of this method include the following:
- An applicable SPF is required for the facility type of interest. It may also be necessary to adjust the SPF through calibration to better reflect local conditions or a different study period.
- Applicable CMFs are required to account for the additional variables of interest.
- It is susceptible to regression-to-the-mean bias (i.e., random variation in crashes over time).

Expected Crash Frequency

This method is used to estimate the crash frequency for design alternatives. The results can be used to compare the safety performance of design alternatives or to quantify the benefits in a benefit-cost analysis. The required inputs for this method include the following:

- Observed crashes from an applicable crash history.
- Predicted crashes from an applicable SPF.
- Engineering judgment.

This method applies to situations where the observed and predicted crashes can be estimated and where the SPF includes the variables of interest. In these cases, the predicted crash frequency is computed from the applicable SPF for the conditions of interest. The expected crash frequency is computed using the Empirical Bayes approach, which is a weighted average of the observed and predicted crashes; this improves the accuracy and reliability of the estimate. The weight is based on the statistical reliability of the SPF.

The advantages of this method include the following:

- It provides an estimate of the change in crash frequency (not just the percent change).
- It can account for changes in traffic volume over time.
- It includes data from the site of interest as well as data from similar sites to reduce the reliance on crash data for any one location.
- It can account for regression-to-the-mean bias (i.e., random variation in crashes over time) by considering the long-term average crash frequency rather than short-term observed crash frequency.

The limitations of this method include the following:

- An applicable SPF is required that includes the variables of interest. For example, the SPF would need to include a variable for median type if this was a design feature of interest. It may also be necessary to adjust the SPF through calibration to better reflect local conditions or a different study period.
- An appropriate level of expertise is required to apply the Empirical Bayes method.

Expected Crash Frequency with CMF Adjustment

This method is used to estimate the crash frequency for design alternatives. The results can be used to compare the safety performance of design alternatives or to quantify the benefits in a benefit-cost analysis. The required inputs for this method include the following:

- Observed crashes from an applicable crash history.
- Predicted crashes from an applicable SPF.
- Applicable CMF(s).
- Engineering judgment.

This method applies to situations where the observed and predicted crashes can be estimated and where the SPF does not include one or more variables of interest. In these cases, the predicted crash frequency is computed from the applicable SPF for baseline conditions and multiplied by applicable CMFs to estimate crashes for the conditions of interest. The expected crash frequency is computed using the Empirical Bayes approach, which is a weighted average of the observed and predicted crashes; this improves the accuracy and reliability of the estimate. The weight is based on the statistical reliability of the SPF.

The advantages of this method include the following:

- It provides an estimate of the change in crash frequency (not just the percent change).
- It can account for changes in traffic volume over time.
- It includes data from the site of interest as well as data from similar sites to reduce the reliance on crash data for any one location.
- It does not require an SPF that includes all variables of interest.
- It can account for regression-to-the-mean bias (i.e., random variation in crashes over time) by considering the long-term average crash frequency rather than short-term observed crash frequency.

The limitations of this method include the following:

- An applicable SPF is required for the facility type of interest. It may also be necessary to adjust the SPF through calibration to better reflect local conditions or a different study period.
- Applicable CMFs are required to account for the additional variables of interest.
- An appropriate level of expertise is required to apply the Empirical Bayes method.

The following table provides a summary of the previous methods along with the required inputs. Note that engineering judgment is an essential component of all methods.

Methods for Quantifying Safety Impacts	Required Inputs			
	Applicable CMF	Applicable Crash History (Observed Crashes)	Applicable SPF (Predicted Crashes)	Engineering Judgment
Relative Comparison of CMFs	•			•
Observed Crash Frequency with CMF Adjustment	•	•		•
Predicted Crash Frequency			•	•
Predicted Crash Frequency with CMF Adjustment	•		•	•
Expected Crash Frequency		•	•	•
Expected Crash Frequency with CMF Adjustment	•	•	•	•

Related Tools for Implementing Methods

Several tools have been developed to help implement the methods presented above. This guide provides a brief introduction to various tools that are available for quantifying safety impacts in the development and analysis of alternatives. Readers can refer to the specific references for more information on each tool.

Highway Safety Manual

The Highway Safety Manual (HSM) provides a new generation of safety analysis methods and represents the current state-of-the-art in highway safety analysis *(7)*. The knowledge and methods included in the HSM may allow users to explicitly consider and quantify safety in the project development process. The HSM includes four parts as follows:

- Part A – Introduction, Human Factors, and Fundamentals: Part A describes the purpose and scope of the HSM and includes the fundamentals and background information needed to apply the methods and tools provided in Parts B, C, and D of the HSM.
- Part B – Roadway Safety Management Process: Part B presents information related to each of the six steps in the safety management process. These steps include network screening, diagnosis, countermeasure selection, economic appraisal, project prioritization, and effectiveness evaluation.
- Part C – Predictive Method: Part C provides a predictive method for estimating expected crash frequency of a network, facility, or individual site. This includes the use of SPFs to estimate the predicted crash frequency. Predictive methods are currently provided for roadway segments and intersections for the following facility types: 1) rural two-lane, two-way roads, 2) rural multilane highways, and 3) urban and suburban arterials. The predictive method for freeways and ramps has been developed and will be incorporated in the next edition of the HSM.
- Part D – Crash Modification Factors: Part D provides a catalog of CMFs for a variety of design and operational strategies. The material is organized by site type and includes CMFs for strategies related to roadway segments, intersections, interchanges, special facilities, and road networks.

With respect to the development and analysis of alternatives, Part B is used to help guide the diagnosis of safety issues and the countermeasure selection process. While safety is currently incorporated in the development and analysis of alternatives, a formal safety diagnosis helps to develop more targeted strategies to address specific safety issues. Part C and Part D are likely the most applicable as SPFs and CMFs are used to quantify and compare the safety impacts of various alternatives. Part C is used to estimate the safety performance of alternatives in terms of crash frequency and severity. Readers can refer to the *Introduction to Safety Performance Functions (6)* for more information on SPFs and how they are applied. For more information on the use of predictive methods to evaluate alternatives, refer to Integrating the HSM into the Highway Project Development Process *(8)*. If the application of this approach is beyond the expertise of the project team, then they could seek assistance from the State Highway Safety Engineer (or equivalent) or the FHWA Division Office.

Contact information for the FHWA field offices is available at: http://www.fhwa.dot.gov/about/field.cfm.

Crash Modification Factors Clearinghouse

The CMF Clearinghouse *(9)* is a web-based database of CMFs with supporting documentation to help users identify the most appropriate countermeasure for their safety needs. Four of the seven methods presented in the previous section rely on CMFs and the CMF Clearinghouse is a good source for this information. Users can search the site for applicable CMFs or submit CMFs to be included in the clearinghouse. The CMF Clearinghouse includes all CMFs from the HSM and many others. While the CMF Clearinghouse provides a wealth of information related to CMFs, sound engineering judgment is paramount to selecting an appropriate value, particularly when there are multiple CMFs for a given treatment. Readers can refer to the *Introduction to Crash Modification Factors (5)* for further guidance on selecting an appropriate CMF. Challenges and opportunities related to the applicability of CMFs are also discussed later in this document in the section titled: *Overcoming Potential Challenges*.

Interactive Highway Safety Design Model

The Interactive Highway Safety Design Model (IHSDM) is a decision-support tool that provides a suite of analysis modules for evaluating the safety and operational impacts of geometric design decisions *(10)*. The predictive methods from Part C of the HSM are included in this free software to help users estimate the safety performance of an existing or proposed facility. Predictive methods are available for rural two-lane highways, rural multilane highways, urban/suburban arterials, and mainline freeway segments. A calibration tool is also available to assist users in implementing the calibration procedures described in Part C of the HSM. Other modules allow users to check existing or proposed highway designs against relevant design policy values, assess design consistency, conduct detailed intersection design reviews, analyze traffic operations, and simulate driver and vehicle factors for two-lane roads.

Interchange Safety Analysis Tool Enhanced

The Interchange Safety Analysis Tool Enhanced (ISATe) is a decision-support tool that provides the ability to estimate the safety impacts of design decisions related to interchanges *(11)*. The tool was developed as part of a larger research effort under the National Cooperative Highway Research Program (NCHRP) Project 17-45, *Enhanced Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges*, to develop predictive methods for freeways and interchanges to be included in future editions of the HSM. The ISATe tool can help users implement the predictive methods for freeway segments, ramps, and ramp terminal intersections.

Selecting an Appropriate Method

It is important to select an appropriate method to assess the safety impacts during the development and analysis of alternatives. The selection of an appropriate method is based on the complexity of the decision at hand and the availability of required inputs. It does not depend on the specific phase of the project development process. For example, the preferred method is to estimate crashes based on the *Expected Crash Frequency with CMF Adjustment*; however, this method requires an applicable crash history and would not apply to new construction projects. As another example, the *Relative Comparison of CMFs* may not be appropriate when there are substantial differences in the fundamental characteristics of the alternatives (e.g., different area type, number of lanes, and/or traffic volume). In such cases, it is necessary to conduct a more detailed analysis, preferably using expected crashes with or without CMF adjustment. The following table is provided to help users select an appropriate method for quantifying safety impacts.

Sample Scenario 1

Compare the safety impacts of alternatives with differences in design elements (e.g., shoulder width)

Question 1

Is an applicable crash history available to estimate the observed crashes for future conditions without treatment?

YES

If NO, go to Question 3

Is an applicable SPF available to estimate predicted crashes for baseline conditions?

YES

If NO, go to Question 5

Is an applicable CMF available to estimate the safety impact of the differences in the design elements (e.g., different shoulder widths)?

YES

If NO, go to Question 2

Go to Expected Crash Frequency with CMF Adjustment

Question 2

Is an applicable crash history available to estimate the observed crashes for future conditions without treatment?

YES

If NO, go to Question 3

Is an applicable SPF available to estimate predicted crashes for the conditions of interest (e.g., does the SPF include a variable for shoulder width)?

YES

If NO, go to Question 3

Go to Expected Crash Frequency below

Sample Scenario 2

Question 3

Is an applicable SPF available to estimate predicted crashes for baseline conditions?

YES

If NO, go to Question 5

Is an applicable CMF available to estimate the safety impact of the differences in the characteristics of the facility type of interest (e.g., is a CMF available for converting a four-lane road to a three-lane road with two-way left-turn lanes)?

YES

If NO, go to Question 4

Go to Predicted Crash Frequency with CMF Adjustment

Expected Crash Frequency with CMF Adjustment

Process Compute the predicted crashes for baseline conditions and multiply by the applicable CMFs to estimate the predicted crashes for the conditions of interest. The expected crash frequency is then estimated using the Empirical Bayes approach.

Applicability[1] Simple and Complex Scenarios

Expected Crash Frequency

Process Compute the predicted crashes for the conditions of interest. The expected crash frequency is then estimated using the Empirical Bayes approach.

Applicability[1] Simple and Complex Scenarios

Predicted Crash Frequency with CMF Adjustment

Process Compute the predicted crashes for baseline conditions and multiply the predicted crashes by the applicable CMFs to estimate the predicted crashes for the conditions of interest.

Applicability[1] Simple and Complex Scenarios

Notes: 1. Simple scenarios include those with minor differences in the overall characteristics of the alternatives (e.g., same area type, number of lanes, and traffic volume). Complex scenarios include those with substantial differences in the overall characteristics of the alternatives (e.g., different area type, number of lanes, and/or traffic volume).

Compare the safety impacts of alternatives with different overall characteristics (e.g., existing four-lane undivided segment and proposed three-lane segment with two through lanes and a two-way left-turn lane)

Sample Scenario 3

Compare the safety impacts of alternatives with different safety treatments (e.g., shoulder widening and shoulder rumble strips)

Question 4

Is an applicable SPF available to estimate the predicted crashes for the conditions of interest (e.g., does the SPF include a variable for number of lanes and median type)?

YES

If NO, go to Question 5

Go to Predicted Crash Frequency

Question 5

Is an applicable crash history available to estimate the observed crashes for baseline conditions (without either treatment)?

YES

If NO, go to Question 6

Are applicable CMFs available to estimate the safety impacts of the conditions of interest (e.g., shoulder widening and shoulder rumble strips)?

YES

If NO, then it is not possible to quantify the safety impacts based on these methods

Go to Observed Crash Frequency with CMF Adjustment

Question 6

Are applicable CMFs available to estimate the safety impacts of the conditions of interest (e.g., shoulder widening and shoulder rumble strips)?

YES

If NO, then it is not possible to quantify the safety impacts based on these methods

Go to Relative Comparison of CMFs

Predicted Crash Frequency

Process Compute the predicted crashes for the conditions of interest.

Applicability[1] Simple and Complex Scenarios

Observed Crash Frequency with CMF Adjustment

Process Compute the observed crashes for baseline conditions and multiply the observed crashes by the applicable CMF to estimate crashes for the two conditions.

Applicability[1] Simple Scenarios

Relative Comparison of CMFs

Process Compare the CMFs to estimate the relative impacts of the two conditions.

Applicability[1] Simple Scenarios

APPLICATION OF CMF-RELATED METHODS IN THE DEVELOPMENT AND ANALYSIS OF ALTERNATIVES

There are several opportunities to quantify safety in the development and analysis of alternatives. The identification of potential safety issues and development of targeted mitigation measures can be accomplished in the identification phase. The actual analysis to quantify and compare safety impacts would occur in the evaluation phase.

This section focuses on the evaluation phase and the application of CMFs to quantify the safety impacts of alternatives. Four of the six methods for quantifying safety impacts involve the use of CMFs. As such, the remainder of this guide focuses on only those methods that apply CMFs in the development and analysis of alternatives as noted below. Examples are provided, followed by a case study and a discussion of opportunities to overcome potential challenges.

Specific applications of CMF-related methods are presented below to demonstrate the use of CMFs to quantify the safety impacts of alternatives. The first demonstrates the *Relative Comparison of Design Alternatives using CMFs*, which uses CMFs alone to compare the anticipated percent change in crashes for various alternatives. The second application, *Estimating the Safety Impacts of Design Decisions using Observed Crashes and CMFs*, is slightly more advanced as CMFs are used within a benefit-cost analysis. The second application demonstrates the use of observed crash history to estimate future crashes for baseline conditions and the application of CMFs to estimate the change in crashes for design alternatives. The estimated change in crashes is then converted to a monetary value based on average crash costs and compared to the project cost to estimate the benefit-cost ratio of the alternative. The results can be used to compare the safety performance of alternatives in terms of estimated crashes or determine whether or not an enhanced design feature or specific mitigation measure is cost-effective. The case studies provide additional examples, including the *Expected Crash Frequency with CMF Adjustment* method. The *Predicted Crash Frequency with CMF Adjustment* method is a component of the *Expected Crash Frequency with CMF Adjustment* method.

Relative Comparison of Design Alternatives using CMFs

The following steps can be used to compare the relative safety impacts of various alternatives in the evaluation phase when the *Relative Comparison of CMFs* is identified as an appropriate method.

Step 1: Identify Applicable CMFs for Conditions of Interest
CMFs are first identified for the various conditions of interest. As discussed in the *Introduction to Crash Modification Factors (5)*, the CMF selection process involves several considerations including the availability of related CMFs, the applicability of available CMFs, and the quality of applicable CMFs. The CMF Clearinghouse *(9)* contains more than 3,000 CMFs for various design and operational features and also provides detailed information for each CMF to help users identify applicable scenarios and the related quality.

Step 2: Combine CMFs to Estimate Overall Impact of Alternatives
One or more features may vary among alternatives. If there is only one feature of interest that varies among alternatives (e.g., presence or absence of rumble strips), then it is not necessary to combine multiple CMFs and the user can proceed with Step 3. If there are multiple features that vary among alternatives (e.g., lane and shoulder width), then it may be necessary to combine multiple CMFs to represent the overall safety impact of each alternative before proceeding to Step 3. As discussed in the *Introduction to Crash Modification Factors (5)*, the current practice assumes that CMFs are multiplicative when the CMFs apply to the same crash type and severity. It is not appropriate to multiply CMFs that do not apply to the same crash type and severity. More information regarding the application of multiple CMFs is available in recent articles *(12, 13)*.

Step 3: Compare CMFs to Quantify Relative Impacts of Alternatives
Once CMFs are identified for the various alternatives and combined as necessary, they can be compared to estimate the relative safety impacts. CMFs indicate the expected change in crashes relative to a certain baseline condition. For example, a CMF may indicate the expected change in crashes if a roundabout is constructed in place of a signalized intersection. In this way, CMFs are used to estimate the benefit of one condition over another. The estimated percent change in crashes is equal to 100*(1-CMF). For example, a CMF equal to 0.95 indicates an expected five percent reduction in crashes.

Example: The following example presents a scenario where a project team is developing and evaluating alternatives for enhancing the safety and operations of an existing two-way stop-controlled intersection. Two alternatives were developed by the study team including a traffic signal and a roundabout. [Note that a traffic signal is warranted based on an engineering study.] As part of the evaluation phase, the study team would like to estimate the potential safety impacts of the two alternatives. The safety impacts can then be considered in conjunction with other factors such as cost and operational impacts. The following table summarizes the conditions for the existing intersection and two alternatives identified for the evaluation phase. The intersecting roadways are rural, two-lane roads with one approach lane per approach and posted speeds of 45 mi/h.

Scenario	Approaches	Traffic Control
Existing Design	4	Two-way stop-control
Alternative 1	4	Traffic signal
Alternative 2	4	Single-lane roundabout

It was determined that a relative comparison of CMFs would be an appropriate method for quantifying the safety impacts of the alternatives because the required inputs and expertise to apply more rigorous methods were not available to the study team. Applicable CMFs were identified from the HSM (7). The following table presents the CMFs for each opportunity along with the baseline condition and applicability. [Note that all CMFs apply to total crashes at rural, four-legged intersections.]

Alternative	CMF	Applicable Facility Type	Applicable Crash Type	Applicable Crash Severity
Convert two-way stop-control to traffic signal	0.56	Rural 4-legged intersection	All	All
Convert two-way stop-control to single-lane roundabout	0.29	Rural 4-legged intersection	All	All

Alternative 1 includes changes to only one feature (i.e., traffic control) compared to the existing design. As such, it is not necessary to combine CMFs (Step 2). Based on the CMF for installing a traffic signal, Alternative 1 is expected to reduce total crashes by 44 percent (100(1-0.56)) compared to the existing design.*

Alternative 2 also includes changes to only one feature (i.e., traffic control) compared to the existing design. As such, it is not necessary to combine CMFs (Step 2). Based on the CMF for installing a single-lane roundabout, Alternative 2 is expected to reduce total crashes by 71 percent (100(1-0.29)) compared to the existing design.*

Based on the relative comparison of CMFs, it appears that either alternative would enhance safety compared to the existing design, but Alternative 2 (single-lane roundabout) is anticipated to have larger safety benefits than Alternative 1 (traffic signal). The potential safety impacts can now be considered in conjunction with other factors such as cost and operational impacts.

Estimating the Safety Impacts of Alternative Designs Using Observed Crashes and CMFs

The previous example is a relatively simple application of CMFs and is useful for estimating the relative safety effects of various alternatives or safety strategies. It does not, however, estimate the change in the *number* of crashes or consider the relative cost of the alternatives. If the number of crashes without treatment is estimated, then the CMFs can be applied to estimate the change in the number of crashes. The change in crashes can then be converted to a monetary value, based on average crash costs, to estimate the value of the benefit (or disbenefit). Finally, these costs can be compared to the construction costs to estimate a benefit-cost ratio. The following example illustrates this process. Further details on the step-by-step process can be found in the companion guide, *CMFs in Practice: Quantifying Safety in the Roadway Safety Management Process (14)*.

Example: Continuing with the previous example, suppose now that the project team would like to determine if either of the alternatives are cost-effective (i.e., benefit-cost ratio greater than 1.0) and, if so, which is more cost-effective. This analysis requires an estimate of the benefit and cost of each alternative in terms of a dollar value. The following table provides a summary of the construction costs, annual operating and maintenance costs, and expected service life for the two alternatives. [Note that these costs would be based on average construction costs provided by the State or local agency.]

Alternative	Construction Cost	Annual Operating and Maintenance Cost	Service Life
Traffic signal	$300,000	$10,000	10
Single-lane roundabout	$900,000	Negligible	20

The five-year average crash frequency for the existing two-way stop-controlled intersection is 10.4 crashes per year. This is used as the estimate of crashes without treatment (i.e., no-build scenario). [Note that more rigorous methods should be used to estimate crashes without treatment when the required inputs are available.]

The CMFs are applied individually to estimate the crashes for each alternative as follows:

*Estimated crashes with treatment = CMF * Estimated crashes without treatment*

Alternative #1: Install traffic signal

*Estimated crashes = 0.56 * 10.4 crashes per year = 5.8 crashes/year*

Alternative #2: Install single-lane modern roundabout

*Estimated crashes = 0.29 * 10.4 crashes per year = 3.0 crashes/year*

The estimated change in crashes per year is calculated as the estimated crashes with treatment minus the estimated crashes without treatment. For the traffic signal, the estimated change in crashes is 4.6 crashes per year (10.4 crashes per year minus 5.8 crashes per year). For the roundabout, the estimated change in crashes is 7.4 crashes per year (10.4 crashes per year minus 3.0 crashes per year).

The dollar value of the annual safety benefit is then computed by multiplying the change in crashes per year by the average cost of a crash. Many agencies have developed or adopted their own crash costs, but national estimates are also available such as those provided by FHWA (15). The HSM (7) also provides comprehensive crash costs by severity level, which are based on the data from the FHWA report, Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries (15). In this case, total crashes were analyzed so the average cost of all crashes is used. The average cost of a crash, including all types and severities, is $32,236 (15). [Note that crash costs vary by type and severity and different costs would apply if the analysis was based on specific crash types or severities. If possible, the analyst should use local crash costs by severity

Note that several methods are available for estimating crashes without treatment. The estimated crash frequency without treatment should correspond with the specific crash type and severity for which the CMF is applicable. If the CMF applies to total crashes, then one should estimate the total annual crashes without treatment. If the CMF applies to a specific crash type or severity, then the annual crashes without treatment should be computed for that crash type or severity.

level.] For the traffic signal, the annual benefit is $148,286 (4.6 crashes per year times $32,236 per crash). For the roundabout, the annual benefit is $238,546 (7.4 crashes per year times $32,236 per crash).

The present value is computed for each treatment using the following equation. This scenario assumes an inflation rate of three percent, and a service life of 10 years for the traffic signal and 20 years for the roundabout. In the following equation, (A) is the annual benefit or disbenefit, (i) is the inflation rate, and (n) is the service life.

$$\text{Present Value} = A * \frac{(1+i)^n - 1}{i * (1+i)^n}$$

The present value of the safety benefits of installing a traffic signal is computed as follows:

$$\text{Present Value of Traffic Signal} = \$148{,}286 * \frac{(1+0.03)^{10} - 1}{0.03 * (1+0.03)^{10}} = \$1{,}264{,}910$$

The present value of the safety benefits of constructing a roundabout is computed as follows:

$$\text{Present Value of Roundabout} = \$238{,}546 * \frac{(1+0.03)^{20} - 1}{0.03 * (1+0.03)^{20}} = \$3{,}548{,}962$$

The benefit-cost ratio is computed as the present value of the benefits divided by the present value of the total project costs. The total project costs include the construction cost plus the present value of annual operating and maintenance costs. Using the equation above, the present value of the annual operating and maintenance cost of the traffic signal is $85,302. For the traffic signal, the benefit-cost ratio is 3.3 ($1,264,910 / $385,302). For the roundabout, the benefit-cost ratio is 3.9 ($3,548,962 / $900,000). From this analysis, it is shown that both treatments are economically justified (benefit-cost ratio greater than 1.0) and the roundabout is more cost-effective (i.e., greater improvement per dollar spent) than the traffic signal. Note that this example focused on total crashes and the results may be different if the analysis focused on fatal and injury crashes.

CASE STUDIES

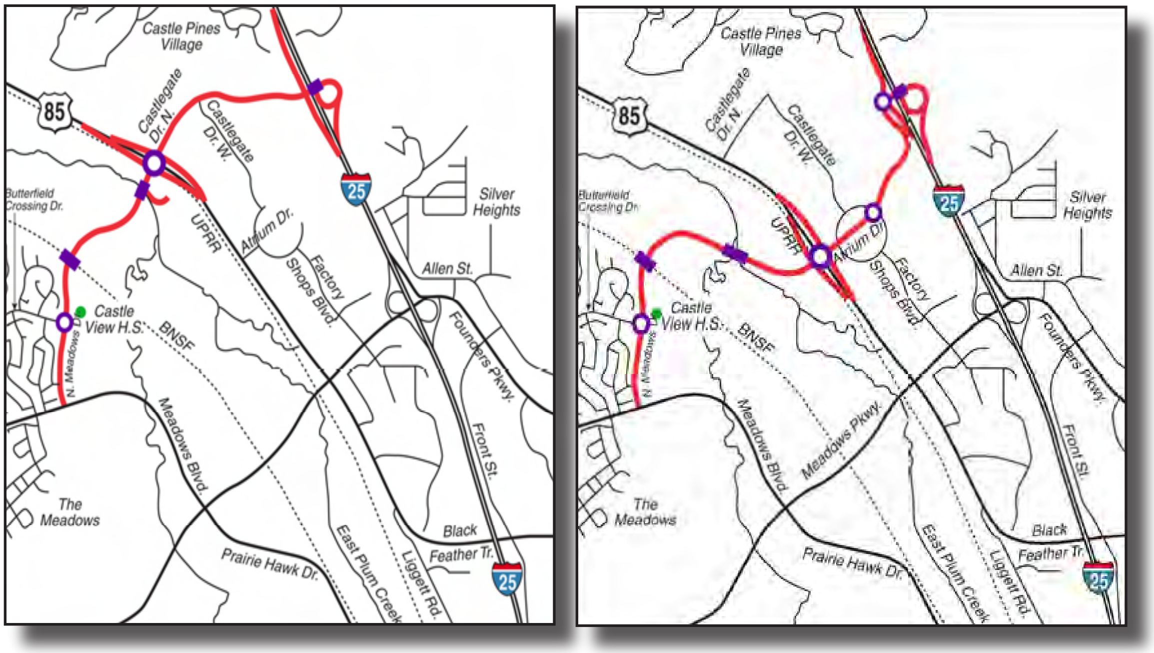
CMFs can be applied in the development and analysis of alternatives to estimate the safety performance when the advantages and disadvantages of each alternative are considered. The following case studies illustrate how CMFs have been applied by the Colorado Department of Transportation (CDOT) and the Arizona Department of Transportation (ADOT) in the development and analysis of alternatives.

Case Study #1: Evaluating Alternatives using Observed Crash Frequency with CMF Adjustment

The following case study illustrates how the *Observed Crash Frequency with CMF Adjustment* method has been used to assess the safety impact of alternatives. Information for the case study was provided by CDOT.

Project Description

Castle Rock, Colorado lies south of Denver along the Interstate 25 corridor. To accommodate growing development in the area, CDOT considered a new interchange on I-25. In addition to the “no build” scenario, they considered two alternatives for the new interchange design (see Figure 1). Alternative 1 would extend one road, Castlegate Drive, to create the new interchange. Alternative 2 would extend another road, Atrium Drive, to create the new interchange.



Alternative 1 (Castlegate Dr extended to I-25)

Alternative 2 (Atrium Dr extended to I-25)

Figure 1. Study Area for Alternatives 1 and 2 *(16)*

As part of the environmental assessment of the project in 2009, CDOT conducted a safety analysis to evaluate the effect on crashes for the proximate roadway segments and intersections, including ramp junctions. The full safety analysis developed estimates of crash predictions for each segment and junction based on either SPFs (for segments) or comparisons to similar intersections in the area (for intersections). At the time of the analysis, CDOT did not have available SPFs for intersections.

Practical Application of CMFs

This case study focuses on two alternative designs for the junction of the I-25 southbound ramp with Castlegate Drive and Atrium Drive. The following explains the process used to generate the safety predictions for the two alternatives.

Step 1 – Identify Alternatives

The two alternatives are presented in Table 1. In Alternative 1, the southbound ramp from I-25 would intersect with Castlegate Drive at a one-way stop-controlled intersection. In Alternative 2, due to the angle of the approaches, the southbound ramp from I-25 would intersect Atrium Drive at a roundabout.

Table 1. List of Alternatives

Alternative	Location	Intersection Type
1	Castlegate Drive	One-way stop-control
2	Atrium Drive	Roundabout

Step 2 – Estimate Traffic Volumes

CDOT estimated total intersection volume for the build-out year of 2030 based on trip generation and distribution models. For both alternatives, the projected volume is 25,000 – 30,000 vehicles per day.

Step 3 – Estimate Base Annual Crash Frequency

CDOT estimated the base annual crash frequency at the ramp junction intersection for both alternatives. As noted above, intersection SPFs were not available at the time of the analysis. Instead, the crash frequency without treatment was estimated from the observed crash histories of nearby intersections that were similar in terms of roadway type and traffic volume. The base annual crash frequency was estimated to be 1.0 to 2.0 crashes per year. A range was used to indicate the potential variability in the results.

Step 4 – Apply CMF

The intersections used to estimate the base crash frequency were all stop-controlled intersections. As such, the results from Step 3 provided an estimate of the annual crash frequency for Alternative 1 (stop-controlled intersection), but not for Alternative 2 (roundabout). To estimate the annual crashes for Alternative 2 (roundabout), CDOT applied a CMF of 0.5 to adjust the base crash frequency from Step 3. The CMF applies to total intersection crashes. Table 2 presents a summary of the two alternatives and the estimated annual crash frequency for the build-out year 2030. In this case, Alternative 2 (roundabout junction) appears to be more favorable than Alternative 1 (stop-controlled junction) with respect to safety for the I-25 southbound ramp junction.

Table 2. Estimated Annual Crash Frequency

Alternative	Intersection Type	Estimated Crashes per Year (Base Estimate)	CMF	Total Crashes per Year (Adjusted Estimate)
1	One-way stop-control	1.0 – 2.0	N/A	1.0 – 2.0
2	Roundabout	1.0 – 2.0	0.5	0.5 – 1.0
Source: Gan, A., Shen, J., and Rodriguez, A., "Update of Florida Crash Reduction Factors and Countermeasures to Improve the Development of District Safety Improvement Projects." Florida Department of Transportation, (2005).				

For more information about the case study, please contact Colorado Department of Transportation, Safety and Traffic Engineering Branch, 303-757-9662.

Summary of Key Findings

This case study presented an example of how CMFs can be applied to estimate the safety impacts of various alternatives. The safety analysis presented in this case study was just one piece of the overall safety analysis conducted for the proposed interchange alternatives. In addition to the safety analysis of the alternative junction types, CDOT developed crash estimates for each segment and intersection within the study area. The result was an estimate of annual crashes for the entire study area for Alternatives 1 and 2. The estimated safety performance of each alternative can then be considered with the operational performance, project costs, environmental impacts, and other factors to identify a balanced design and the most desirable alternative.

Case Study #2: Evaluating Alternatives using Predicted Crash Frequency with CMF Adjustment

The following case study illustrates how the *Expected Crash Frequency with CMF Adjustment* method has been used to quantify the safety impacts during the development and analysis of alternatives. Information for the case study was provided by ADOT.

ADOT is performing predictive analyses following the procedures in the AASHTO Highway Safety Manual *(7)* at the scoping and alternative selection stage of demonstration projects. They are working to develop a framework for integrating substantive safety considerations into the ADOT project planning and development process.

Project Description

ADOT identified potential safety improvements on a 24.6 mile section of Arizona State Route 264 (SR 264) and evaluated the potential safety impacts during the analysis phase of the development and analysis of the alternatives. SR 264 is a rural, two-lane road in northeastern Arizona and functionally classified as a minor arterial. Figure 2 identifies the general location and limits of the study section.

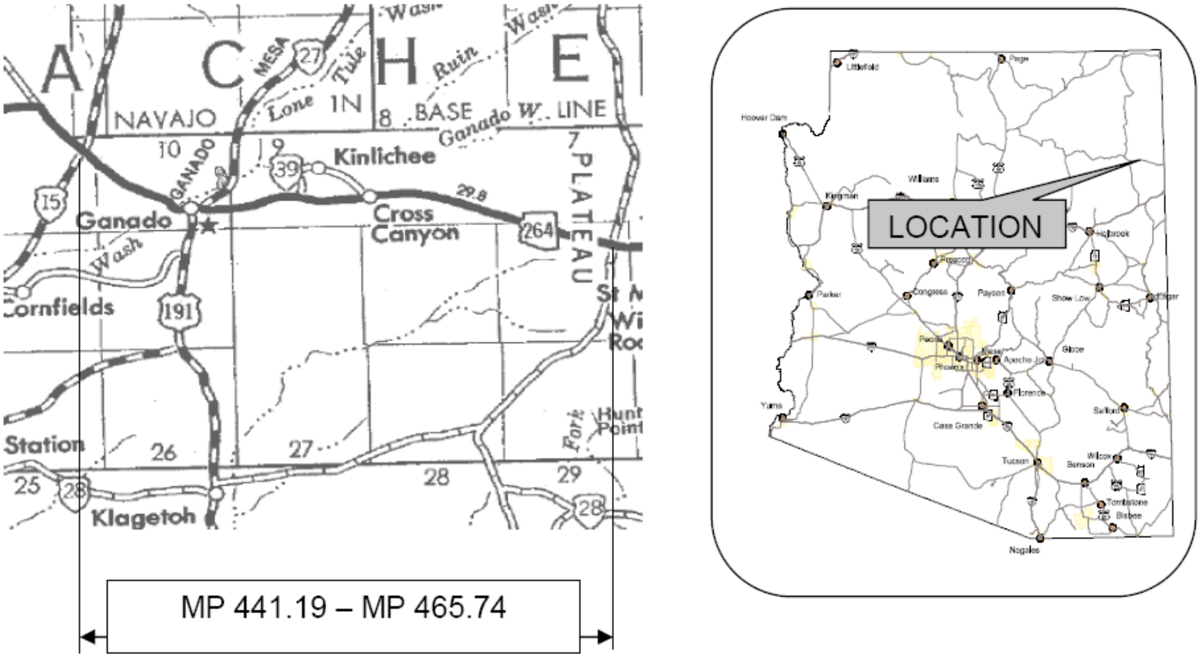


Figure 2. SR 264 Section of Interest *(17)*

The existing roadway is characterized by a narrow cross-section with 12-ft lanes, 1-ft or less paved shoulders, and intermittent turn lanes and passing lanes. The traffic volume for 2010 ranged from 4,100 to 6,400 within the study section. Proposed improvements included widening the shoulder, adding centerline and shoulder rumble strips, adding delineators and recessed pavement markers, flattening side slopes, installing guardrail, and extending drainage structures. It was determined that all improvements would be implemented, but the optimal shoulder width was in question. As such, ADOT considered two alternatives with different shoulder widths.

ADOT considered a 20-year scenario (2016-2036) and the study section was divided into homogenous segments for analysis. A homogeneous segment has similar roadway, roadside, and operational characteristics. For example, a new segment would be created where there was a change in traffic volume. The segmentation resulted in 242 homogenous segments. Each of the segments was analyzed separately and the results were combined to estimate the safety performance of the entire study section under the various conditions. For this case study, the calculations are shown for the first tangent segment and the results are summarized for the study section as a whole. The 2016 baseline conditions and proposed alternatives for Segment 1 are summarized in Table 3 as per the conditions considered in the HSM Part C Predictive Methods for Rural Two-Lane Two-Way Roads *(7)*. Notable differences among the scenarios of interest include the following:

- Shoulder width: The 2016 baseline condition would include 1-ft paved shoulders while the two alternatives would include 5-ft and 8-ft paved shoulders, respectively.
- Presence of centerline rumble strips: The 2016 baseline condition would not include centerline rumble stripes while the two alternatives would both include centerline rumble stripes.
- Roadside hazard rating: The 2016 baseline condition would have a roadside hazard rating of 6, which is characterized by a clear zone width less than or equal to 5 feet, non-recoverable sideslope (1V:2H), and exposure to rigid roadside obstacles (offset 0 to 6.5 feet) without guardrail. The two alternatives would both include roadside improvements to upgrade the roadside hazard rating to 2, which is characterized by a clear zone width between 20 and 25 feet and recoverable sideslope (1V:4H).

Table 3. Summary of Existing and Alternative Conditions for Segment 1 (Tangent)

Roadway Characteristics	2016 Baseline	Alternative 1	Alternative 2
Traffic volume	4,350	4,350	4,350
Length (mi)	0.16	0.16	0.16
Lane width (ft)	12	12	12
Shoulder width (ft)	1	5	8
Shoulder type	Paved	Paved	Paved
Horizontal curve	No	No	No
Grade (%)	0	0	0
Driveway density (driveways/mi)	0	0	0
Centerline rumble strips (yes/no)	No	Yes	Yes
Passing lanes (1 lane / 2 lanes / no)	No	No	No
Two-way left-turn lane (yes/no)	No	No	No
Roadside hazard rating (1-7 scale)	6	2	2
Segment lighting (yes/no)	No	No	No
Auto speed enforcement (yes/no)	No	No	No

Practical Application of Expected Crash Frequency with CMF Adjustment

For this analysis, ADOT utilized the HSM Part C Predictive Methods for Rural Two-Lane Two-Way Roads. ADOT employed the Interactive Highway Safety Design Model (IHSDM) to carry-out the computations for the various scenarios *(10)*.

Using the predictive method, a user specifies an SPF for baseline conditions and applies CMFs to adjust the baseline prediction to reflect other conditions of interest. In this case, the SPF for baseline conditions is given by Equation {1} and the baseline conditions are summarized above in Table 3 *(7)*.

$$N_{SPF} = AADT * L * 365 * 10^{-6} * e^{-0.312} \qquad \{1\}$$

Where:
N_{SPF} = Predicted total crash frequency for baseline conditions.
AADT = Annual average daily traffic volume (vehicles per day).
L = Segment length (mi).

Applying Equation {1} to the existing conditions with an AADT of 4,350 vehicles per day and a segment length of 0.16 miles, the predicted total crash frequency for the baseline conditions is computed as follows:

$$N_{SPF} = 4{,}350 * 0.16 * 365 * 10^{-6} * e^{-0.312}$$

$$N_{SPF} = 0.19 \text{ crashes per year}$$

CMFs were then identified to reflect the conditions of interest. The HSM Part C Predictive Method for Rural Two-Lane Two-Way Roads provides specific CMFs for use with the SPF from Equation {1}. The CMFs are provided in Table 4 *(7)*.

IHSDM is a suite of software analysis tools for evaluating the safety and operational effects of geometric design elements. IHSDM includes six modules, including a Crash Prediction Module (CPM) that is a faithful implementation of the HSM Part C Predictive Methods for Rural Two-Lane Two-Way Roads. The CPM estimates crash frequency and severity given a highway's geometric design and traffic characteristics.

Table 4. Summary of CMFs for Conditions of Interest for Segment 1

Roadway Characteristics	2016 Baseline	Alternative 1	Alternative 2
Lane width	1.00	1.00	1.00
Shoulder width	1.23	1.04	0.93
Shoulder type	1.00	1.00	1.00
Horizontal curves	1.00	1.00	1.00
Grades	1.00	1.00	1.00
Driveway density	1.00	1.00	1.00
Centerline rumble strips	1.00	0.94	0.94
Passing lanes	1.00	1.00	1.00
Two-way left-turn lane	1.00	1.00	1.00
Roadside design	1.22	0.94	0.94
Lighting	1.00	1.00	1.00
Automated speed enforcement	1.00	1.00	1.00
* Note that Part C of the HSM does not include a CMF for shoulder rumble strips. Instead, an appropriate CMF would be identified and applied to the final estimate to reflect the expected safety impacts of the shoulder rumble strips.			

Note that CMFs should only be multiplied if they apply to the same crash type and severity. In this case, all CMFs apply to total crashes.

The CMFs were then combined to estimate the overall safety impact of the conditions of interest. As recommended in the HSM *(7)*, the CMFs were multiplied using Equation {2} to estimate the cumulative effect of the combined treatments for each scenario.

$$CMF_{Combined} = CMF_1 * CMF_2 * \ldots * CMF_n \qquad \{2\}$$

Where:
CMF_i = Crash modification factor for individual roadway characteristic (i).
n = Number of individual roadway characteristics.

The calculations for the combined CMFs are shown below. Note that several of the CMFs are 1.00 and are summarized by 1.00 raised to a power in the calculations. The combined CMFs for the 2016 baseline conditions, Alternative 1, and Alternative 2 are 1.50, 0.92, and 0.82 respectively.

$$CMF_{Combined}\ (2016\ Baseline) = 1.23 * 1.22 * 1.00^{10} = 1.50$$

$$CMF_{Combined}\ (Alternative\ 1) = 1.04 * 0.94 * 0.94 * 1.00^{9} = 0.92$$

$$CMF_{Combined}\ (Alternative\ 2) = 0.93 * 0.94 * 0.94 * 1.00^{9} = 0.82$$

The predicted crash frequency for the baseline conditions is adjusted with the combined CMFs, using Equation {3} to estimate the predicted crashes for the conditions of interest.

$$N_{Predicted} = N_{SPF} * CMF_{Combined} \qquad \{3\}$$

Where: $N_{Predicted}$ = Predicted total crash frequency for conditions of interest.

Computations for the three scenarios of interest are shown below and summarized in Table 5. Note that the baseline predicted crashes are identical for the three scenarios.

$N_{Predicted}$ (2016 Baseline) = 0.19 $*$ 1.50 = 0.29

$N_{Predicted}$ (Alternative 1) = 0.19 $*$ 0.92 = 0.17

$N_{Predicted}$ (Alternative 2) = 0.19 $*$ 0.82 = 0.16

Table 5. Summary of Computations for Predicted Annual Crashes for Segment 1

Scenario	N_{SPF} Equation {1}	$CMF_{Combined}$ Equation {2}	$N_{Predicted}$ Equation {3}
2016 Baseline	0.19	1.50	0.29
Alternative 1	0.19	0.92	0.17
Alternative 2	0.19	0.82	0.16

The ***predicted*** crash frequency was computed for each of the 242 homogeneous segments for each year of the study period (2016 – 2036). The predicted crashes were then combined to estimate the total predicted crashes for the study section over the 20-year analysis period. Finally, the ***observed*** crash history was incorporated, using the Empirical Bayes method, to estimate the ***expected*** number of crashes for the study section. Recall that ***expected*** crash frequency is a weighted average of the ***observed*** crash history and the ***predicted*** crashes. ADOT conducted additional analyses to predict the number of crashes by severity using Part C of the HSM. Instead of using crash severity proportions provided in the HSM ADOT developed its own proportions using crash data from similar roadways within the Navajo Nation and Hopi Tribal land. Table 6 presents a summary of expected crashes for the baseline conditions and alternatives.

Table 6. Expected Crashes by Severity for SR 264 Study Section from 2016-2036

Crash Severity	2016 Baseline	Alternative 1	Alternative 2
Total crashes	636.38	531.58	504.16
Fatal and injury crashes	283.40	230.45	216.80
Property damage only crashes	352.98	301.13	287.36

Based on the expected crashes, both alternatives are expected to perform better than the baseline conditions. Alternative 1 is expected to reduce total crashes by 104.8 crashes over the 20-year study period. This represents a 16 percent reduction in expected total crashes. Alternative 2 is expected to reduce total crashes by 132.2 crashes over the 20-year study period. This represents a 21 percent reduction in expected total crashes.

A formal benefit-cost analysis was conducted to determine whether or not the additional shoulder width for Alternative 2 was worth the added project cost. The benefits were estimated by converting the crash savings to a dollar value based on average crash costs used by ADOT and FHWA Arizona Division. The benefit-cost ratio for Alternative 1 was 2.30 and the benefit-cost ratio for Alternative 2 was 1.90. Note that both alternatives have a benefit-cost ratio greater than 1.0,

Note that a calibration factor can also be applied to account for jurisdictional/regional variations such as driver population, weather, and crash reporting. At the time of this case study, ADOT had not developed a local calibration factor. As a result, a local calibration factor of 1.0 was assumed.

It is preferred to use calibrated SPFs for computing predicted crashes to compare alternatives or to use in an economic analysis. Non-calibrated SPFs may overestimate or underestimate the predicted crash frequency, but provide a reasonable estimate of the percent difference in crashes among alternatives.

indicating that either option will provide a positive return on investment. Without funding constraints, the preferred alternative would be to widen the roadway to 8-foot shoulders as it would result in the largest reduction in crashes. However, given the number of miles of highway in need of improvement and a limited budget, it was determined that Alternative 1 is the preferred option as it maximizes the return on each dollar spent.

For more information about the case study, please contact Kohinoor Kar, Arizona Department of Transportation; Transportation Safety Engineer; kkar@azdot.gov; 602-712-6857.

Summary of Findings

This case study presented an example of how the *Expected Crash Frequency with CMF Adjustment* method can be used to estimate the expected safety impacts of various design alternatives. ADOT used SPFs and CMFs from the HSM in this analysis, supported by the IHSDM software. They also incorporated observed crash history, using the Empirical Bayes method, to estimate the expected crashes for various scenarios. The result was an estimate of total expected crashes for the entire study section over a 20-year analysis period. This allowed for a quantitative comparison of the safety performance for two design alternatives and the existing conditions. ADOT used the results of the crash analysis in a benefit-cost analysis to help select the most cost-effective alternative.

"Arizona DOT has found that using a predictive method with SPFs and CMFs on cases like this alternatives analysis is more reliable for estimating quantitative safety performances of future scenarios. SPFs give us a tool to predict the future safety performance of a facility without relying strictly on the past 3-5 years of crash data. We have also combined the SPF predictions with actual crash history using the Empirical Bayes method to estimate the expected crashes for a given facility. We have been using crash reduction factors for over 10 years [and CMF Clearinghouse since 2011], and we have recently begun to integrate the HSM predictive methods in our safety projects." *(18)*

OVERCOMING POTENTIAL CHALLENGES

Potential challenges may arise when quantifying safety in the development and analysis of alternatives. Some are directly related to limitations in the progress of safety research, while others apply to a lack of training. General challenges related to limitations in the progress of safety research include availability of CMFs, applicability of CMFs, and estimating the effects of multiple treatments. Specific challenges related to the quantification of safety in the development and analysis of alternatives include insufficient expertise (i.e., understanding how to select and apply appropriate methods) and complex scenarios.

Availability of CMFs

A general challenge is the availability of CMFs for specific countermeasures. The CMF Clearinghouse *(9)* contains over 3,000 CMFs for a wide range of safety countermeasures under a variety of conditions. However, CMFs are still lacking for a large number of treatments, especially combination treatments and those that are innovative and experimental in nature. Furthermore, CMFs may not be available for certain crash types and severities.

The following table provides a summary of the design elements and mitigation measures for which the safety impacts can be assessed using the predictive method and CMFs in Part C of the HSM. Other CMFs are available in the CMF Clearinghouse *(9)* and recently completed research studies such as NCHRP Project 17-45 *(11)*. Additional research is underway to develop CMFs for other design elements and facility types where CMFs are currently unavailable. For example, NCHRP Project 17-53, *Evaluation of the 13*

Controlling Criteria for Geometric Design, is developing CMFs to help fill-in current gaps for several of the priority design criteria.

The CMF Clearinghouse *(9)* provides a "Most Wanted List" for CMFs. Users can access the website and add to the list by submitting ideas for future CMF research or current needs. While the research would need to be completed, this link provides users with the opportunity to share their CMF needs.

Design Element	Rural 2-Lane	Rural Multilane	Urban/Suburban Arterials
Segments			
Lane Width	•	•	
Shoulder Width	•	•	
Shoulder Type	•	•	
Horizontal Alignment	•		
Vertical Alignment	•		
Driveway Density	•		
Centerline Rumble Strips	•		
Passing Lanes	•		
Short Four-Lane Section	•		
Two-Way Left-Turn Lane	•		
Roadside Hazard Rating	•		
Lighting	•	•	•
Automated Speed Enforcement	•	•	•
Median Type		•	•
Median Width		•	•
Side Slopes		•	
On-Street Parking			•
Number of Lanes			•
Roadside Fixed-Objects			•
Intersections			
Number of Intersection Legs	•	•	•
Traffic Control Type	•	•	•
Intersection Skew Angle	•	•	
Left-Turn Lanes	•	•	•
Right-Turn Lanes	•	•	•
Lighting	•	•	•
Left-Turn Phasing			•
Right-Turn on Red			•
Red Light Cameras			•
Bus Stops			•
Schools			•
Alcohol Sales Establishments			•

Applicability of CMFs

CMFs are developed based on a sample of sites with specific conditions. While a CMF may be available for a given treatment, it may not be appropriate for the scenario under consideration. For example, there may be significant differences between the characteristics of a proposed treatment site and the sites used to develop the CMF (e.g., different area type, number of lanes, or traffic volume). The HSM *(7)* and CMF Clearinghouse *(9)* provide information to help users identify the applicability of CMFs.

A related challenge may be that multiple CMFs exist for the same treatment and conditions. This is particularly challenging when multiple studies have estimated CMFs for the same strategy and combination of crash type and severity level, but yielded dissimilar results. If the CMFs also apply to the same roadway characteristics, then the selection can become even more difficult. A star quality rating—which appraises the overall perceived reliability of a CMF using a range of one to five stars—is provided by the CMF Clearinghouse and may be helpful in these circumstances to identify the most suitable CMF. However, the ratings of the different CMFs may be similar as well. If the various CMFs have a fairly small range of values, then this situation may not be of great concern. Yet, it is possible for the CMFs to vary significantly and even have contradictory anticipated outcomes (i.e., some CMFs greater than 1.0 and others less than 1.0). In such cases, this potential situation would be highly challenging to overcome. Additional guidance on how to select the most applicable CMF is posted on the CMF Clearinghouse *(9)* under FAQs.

CDOT indicated that CMFs are typically obtained from FHWA resources such as the CMF Clearinghouse, the Desktop Reference for Crash Reduction Factors, information packets on specific features like roundabouts, and case studies. They have also used these resources to develop an "in-house" list of CMFs for common strategies such as roundabouts. This reduces the effort to search for CMFs during the project development process and also helps to maintain consistency among analyses.

Estimating the Effects of Multiple Treatments

The current practice for many agencies is to assume that CMFs are multiplicative; this is the current method presented in the HSM *(7)* and posted on the CMF Clearinghouse *(9)*. There are relatively few studies that estimate CMFs for combinations of countermeasures. It is far more common for studies to estimate CMFs for individual treatments. Consequently, it is difficult to accurately estimate the effects of combinations of treatments. In brief, the recommended approach may overestimate or underestimate the true crash effects, particularly if the treatments target similar crash types. More information regarding the application of multiple CMFs is available in recent articles *(12, 13)*.

Insufficient Expertise

A specific challenge for the project team could be that there is insufficient expertise within the team to quantify safety impacts using CMFs and related methods. The HSM and related resources are relatively new tools. As such, they have only recently gained popularity among transportation professionals and their use has been mostly limited to applications within the roadway safety management process. There are a number of opportunities to quantify safety impacts in other aspects of the project development process (e.g., development and analysis of alternatives), but it may be necessary to solicit input or assistance from those who are more familiar with the selection and application of CMFs and related methods. If the study team does not have the needed expertise, then they can solicit outside expertise from the State Highway Safety Engineer (or equivalent), FHWA Division Office, or consultants for further guidance and assistance with the selection and/or

Contact information for the FHWA field offices is available at: http://www.fhwa.dot.gov/about/field.cfm.

application of CMF-related methods and interpretation of results. The National Highway Institute also offers several courses related to the quantification of safety using CMFs, including the *Application of CMFs* (#380093) and *Science of CMFs* (#380094).

Complex Scenarios

Another potential challenge is that certain methods (i.e., *Relative Comparison of CMFs*) are not appropriate to analyze complex scenarios. For example, a relative comparison of CMFs may not be appropriate when there are significant differences among the alternatives (e.g., different area type, number of lanes, and/or traffic volume). In these cases, it would be necessary to apply more rigorous methods to estimate the safety performance for each scenario separately. A decision-support table is provided in the section titled: *Selecting an Appropriate Method,* to help users identify an appropriate method for quantifying safety impacts. For more information on predictive methods, refer to Part C of the HSM *(7)* and related documentation, Integrating the HSM into the Highway Project Development Process *(8)*.

CDOT has and continues to incorporate safety estimates in many areas of their transportation planning and design processes. They continue to push forward with development of new SPFs based on data in their state and identification of CMFs that are useful and relevant to their operations. David Swenka (CDOT, safety and traffic engineer), stated that "the application of CMFs for this assessment in concert with other prediction models (i.e., SPFs) was both a necessary and effective way in establishing crash projections for a multitude of proposed alternatives with a variety of different geometric configurations. We have and will continue to rely on the credibility that comes inherent with accepted CMFs developed through empirically based research." *(19)*.

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For More Information:

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