Using CMFs to Quantify the Safety Performance of Design Decisions and Exceptions

The Crash Modification Factors (CMFs) in Practice: Using CMFs to Quantify the Safety Performance of Design Decisions and Exceptions guide describes and illustrates several opportunities to incorporate the latest methods to quantify safety in the design process using CMFs. The target audience includes those who are responsible for developing, reviewing, and approving designs and design exceptions. The purpose of this guide is to help raise awareness of opportunities to consider and quantify the safety impacts of design decisions, with a specific focus on the application of CMFs to support the design 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, designers will be better prepared to assess the safety impacts of individual design elements and evaluate the overall impact of design exceptions on the safety performance of a facility.

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.

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 the safety impacts of design decisions and exceptions. 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 design process to understand the importance of quantifying safety and using appropriate methods to do so.

A design exception is a documented decision to select a value for a roadway feature that does not meet minimum values or ranges established for a particular project. Safety is explicitly considered in the development and evaluation of design exceptions, but has traditionally centered on a qualitative review. Recently developed methods may allow the project team to quantify the safety impacts of individual design elements and proposed design exceptions on the safety performance of the facility. These methods may also provide a means to quantify the potential benefit of contemplated mitigation measures.

The 13 controlling criteria include design speed, lane width, shoulder width, bridge width, horizontal alignment, superelevation, vertical alignment, grade, stopping sight distance, cross slope, vertical clearance, lateral offset to obstruction, and structural capacity.

CONTENTS

Read more for an overview of quantifying safety impacts of design decisions and exceptions or skip to the section that describes available methods for quantifying safety using crash modification factors (CMFs). A decision-support chart is provided to help identify when CMF-related methods may be appropriate in the design process. Examples are provided to illustrate how these methods can be applied and case studies illustrate how these methods have been applied in a particular state to quantify the safety impacts of design decisions and exceptions. 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.

OVERVIEW OF SAFETY IN DESIGN AND DESIGN EXCEPTIONS

According to Federal regulation, the FHWA is responsible for establishing design standards for the National Highway System (NHS)—a network of approximately 220,000 miles of roads deemed vital to the Nation's economy, defense, and mobility. Any roadway project on this system that proposes a design value that fails to meet the minimum criteria set forth in these standards must be approved by FHWA as a design exception. State and local transportation agencies are responsible for addressing any design exceptions, waivers, or variances for roadway projects outside of the NHS.

In general, 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" (1). Documentation of the design exception is critical for establishing a historical record for future reference. Documentation is particularly critical during litigation, as it provides evidence that the decision was made only after thoughtful and thorough review and consideration of design alternatives. Agencies can demonstrate that safety was explicitly considered by quantifying the safety impacts of individual design elements and evaluating the impact of the proposed design exception on the overall safety performance of the facility compared to existing conditions and the scenario that meets or exceeds design standards.

The term "design exception" is frequently used specifically when dealing with controlling criteria, while terms such as "design variance" or "design waiver" are used when dealing with other design criteria. A controlling criterion is one of the 13 design elements identified by the FHWA as having substantial importance to the operational and safety performance of any highway. As such, a design exception commonly refers to the formal means of applying for approval to design one or more controlling criteria below current design standards. The 13 controlling criteria are listed in the *Federal-Aid Policy Guide (1)* and described in FHWA's *Mitigation Strategies for Design Exceptions (2)*.

While the process may vary for state and local agencies, the design exception process adopted by FHWA consists of the following six specific steps (2).
1. Determine Costs and Impacts of Meeting Design Criteria.
2. Develop and Evaluate Multiple Alternatives.

3. Evaluate Risk.
4. Evaluate Mitigation Measures.
5. Document, Review, and Approve.
6. Monitor and Evaluate In-Service Performance.

The six-step process is described below, noting the steps where safety considerations and analysis can be incorporated. By quantifying safety, agencies can better understand the potential impacts of individual design elements and the impacts of a proposed design exception on the overall safety performance of a facility. This is particularly useful for risk management and defending against potential litigation. For example, environmental or right-of-way restrictions may induce a project team to consider design alternatives and perhaps design exceptions to the established design criteria for a given project. Quantifying safety impacts will help to select the design that achieves a reasonable balance between cost, safety, operations, and other impacts.

Determine Costs and Impacts of Meeting Design Criteria

Once the potential for a design exception is identified, the design exception process begins with an estimation of the costs and impacts of designing the roadway element to meet or exceed the design standard. This provides a baseline for the project team to compare the cost and impacts of other design options. This is the first opportunity to employ CMF-related methods to quantify safety in the design exception process.

Develop and Evaluate Multiple Alternatives

If meeting design standards is deemed to be infeasible for a given location, then alternatives should be developed and evaluated. The alternatives should be devised in a way that strives to balance safety, mobility, cost, and impacts. Once developed, each alternative should be evaluated in terms of these considerations, and its performance should be compared relative to the other alternatives and relative to the scenario that meets the design standard.

Safety is explicitly considered in the design exception process, but has traditionally involved a qualitative review. The qualitative review may include a summary of the crash history and a discussion of the anticipated effects of the design exception (e.g., a standard four-foot shoulder will provide more room for recovery than would a proposed two-foot shoulder). The methods discussed in this guide may help quantify the safety impacts of individual design elements and the overall impact of proposed design exceptions on the safety performance of the facility (e.g., lane departure crashes are anticipated to increase by 13 percent with a proposed two-foot shoulder compared to a standard four-foot shoulder for a rural, two-lane road carrying 2,500 vehicles per day). Safety impacts can then be converted to a dollar value based on average crash costs. In this way, safety is quantified and can be considered with other factors such as cost, operational effects, and environmental impacts.

Evaluate Risk

Before proceeding with a proposed design exception, an agency must evaluate the degree to which the risk of safety and/or operational problems could increase or decrease. The results from the previous step can be used to compare the estimated safety performance of proposed design exceptions with the scenario of meeting the design standard. This will provide an indication of the estimated difference in safety performance. The safety performance of a proposed design exception could also be compared to the safety performance of existing conditions to demonstrate the intent to improve safety, even though the design does not meet the design standard.

Evaluate Mitigation Measures

Once the need for a design exception is identified and the potential safety and operational impacts are defined, the next step is to identify and evaluate mitigation measures. Examples of mitigation measures include advance notice to the driver or augmenting the geometric design of other roadway elements to help offset the potential negative effects of the design exception. Mitigation techniques for the 13 controlling criteria are provided in FHWA's *Mitigation Strategies for Design Exceptions (2)*.

The documentation of a design exception typically includes a generic discussion of proposed mitigation measure(s) and the potential to offset the possible negative impacts of the design feature. The CMF-related

methods discussed in this guide can be used to quantify the safety impacts of proposed mitigation measures or combinations of mitigation measures. The results from the safety analysis can be combined with average crash costs and compared to treatment costs to estimate the cost-effectiveness of each potential mitigation measure. This is useful in selecting the final measure(s) to implement, particularly when there are multiple potential mitigation measures.

Document, Review, and Approve

The next step in the process is the documentation, review, and approval of the design exception. Documentation is critical for establishing a historical record and demonstrating that the decision was made only after thoughtful and thorough examination of design alternatives and potential costs and impacts. Important aspects to document include the estimated cost, safety performance, and other potential impacts for several scenarios, including existing conditions, design exception, and scenario of meeting the design standard.

Monitor and Evaluate In-Service Performance

The final step of the process is to monitor and evaluate the safety and operational performance of the facility after completion of the construction project. A thorough review and analysis of safety performance should be conducted for locations where a design exception was implemented for a given roadway element. This will provide important information for future decisions related to similar design considerations.

METHODS FOR QUANTIFYING THE SAFETY IMPACTS OF DESIGN DECISIONS AND EXCEPTIONS

There are several opportunities to identify and address safety impacts in the design process. This section focuses on the evaluation of design decisions and exceptions as well as potential mitigation measures. Several methods and related tools are available to compare the safety impacts of individual design elements and the impacts of design exceptions on the safety performance of a facility. Safety impacts are quantified by estimating the extent to which a design alternative is likely to impact the frequency and severity of crashes. The safety impacts can then be compared among the design 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.

The estimated cost, safety performance, and other potential impacts should be documented for the existing conditions, design exception, and design standard.

Note that while there are several methods available to consider and quantify the safety impacts of design decisions and exceptions, 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 *(3)*.

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 a SPF can be multiplied by an applicable CMF to account for differences between the actual site conditions and the specified baseline conditions. If a 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 (4)* 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 crash history 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 crash history 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 a design element or exception 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 design process. The following is a detailed discussion of the various methods, 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 element. For example, a CMF may be identified for the radius of curve and used to estimate the percent change in crashes when the radius is changed from 300 to 400 feet. CMFs are also used to compare the relative safety benefits of potential mitigation measures when selecting a strategy to address an identified safety issue. For example, CMFs may be identified for shoulder widening and shoulder rumble strips to determine which would likely be more effective in reducing total crashes. 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. While quality CMFs are available for many traffic control strategies and design elements, they are not currently available for all 13 controlling criteria. CMFs related to the 13 controlling criteria are further discussed in *Availability of CMFs* in the *Overcoming Potential Challenges* section, including existing CMFs and efforts to develop additional 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 design elements or mitigation measures 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.

While quality CMFs are available for many traffic control strategies and design elements, they are not currently available for all 13 controlling criteria.

• 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 element 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 for scenarios with different design values (e.g., design standard and design exception). 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 Design Decisions using Observed Crashes and CMFs* section, comparing the cost-effectiveness of various shoulder widths.

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 shoulder width 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 shoulder width. The SPF would be used to estimate the predicted crashes for baseline conditions and CMFs would be applied to estimate the impacts of different shoulder widths.

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 a 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 shoulder width 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 a 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 design process. 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 *(5)*. The knowledge and methods included in the HSM will 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 design exception process, Part B is used to help guide the diagnosis of safety issues and selection of mitigation measures. While safety is currently incorporated in the design exception process, 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 design alternatives. Part C is used to estimate the safety performance of design alternatives in terms of crash frequency and severity. The CMFs from Part D are used to assess the safety impacts of individual design elements or mitigation measures. Readers can refer to the *Introduction to Safety Performance Functions (4)* for more information on SPFs and how they are applied. For more information on the use of predictive methods to evaluate design decisions, refer to *Integrating the HSM into the Highway Project Development Process (6)*. 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 *(7)* 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 (3)* 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 *(8)*. 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 *(9)*. 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 design process. 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 design 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)

Sample Scenario 2

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

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	**Question 5**	**Question 6**
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)?	Is an applicable crash history available to estimate the observed crashes for baseline conditions (without either treatment)?	Are applicable CMFs available to estimate the safety impacts of the conditions of interest (e.g., shoulder widening and shoulder rumble strips)?

Question 4

YES / If NO, go to Question 5

Go to Predicted Crash Frequency

Question 5

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

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 DESIGN PROCESS

There are several opportunities to quantify the safety impacts of design decisions and exceptions. For design decisions, the safety impacts can be compared for different values of a particular design element. For design exceptions, the safety performance can be estimated and compared for various scenarios such as the existing conditions, proposed design exception, and design standard. When comparing the safety performance of various scenarios, potential safety issues can be identified along with potential mitigation measures.

This section focuses on the application of CMFs to quantify the safety impacts of design decisions, including the impact of design elements and potential mitigation measures. 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 design process 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 design elements and mitigation measures. The first demonstrates the *Relative Comparison of Design Alternatives using CMFs*, which uses CMFs alone to compare the anticipated percent change in crashes for different values for a given design element. 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 third application focuses on the *Assessment of Mitigation Measures*. The results can be used to compare the safety performance of design 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 use of more rigorous methods (i.e., Predicted Crash Frequency with CMF Adjustment) to quantify the safety impacts of design alternatives.

Relative Comparison of Design Alternatives using CMFs

The following steps can be used to compare the relative safety impacts of design alternatives 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 (3)*, 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 *(7)* 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 Design Alternatives
One or more features may vary among design alternatives. If there is only one feature of interest that varies among design alternatives (e.g., shoulder width), 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 design 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 (3)*, 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 *(10, 11)*.

Step 3: Compare CMFs to Quantify Relative Impacts of Design 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 spiral transition is constructed compared to the condition without a spiral transition. In other cases, there may be multiple potential values for a given design element (e.g., shoulder width) and the CMFs indicate the expected change in crashes relative to

a baseline shoulder width. 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 design engineer is comparing various shoulder widths as part of a reconstruction project on a rural, two-lane, undivided collector with a posted speed limit of 45 mi/h and an annual average daily traffic volume of 10,000 vehicles per day.

The existing road has no paved shoulders, and the designer has proposed to increase the shoulder width to 2 feet as part of a widening project to address single-vehicle run-off-road crashes. The applicable design standard for this road calls for a shoulder width of 4 feet, but this has been deemed infeasible due to right-of-way constraints and environmental impacts. As such, the designer is filing a design exception to document the reasons for providing 2-ft shoulders and the anticipated safety impacts. The following table summarizes the conditions for the existing design, proposed design, and design standard.

Scenario	Shoulder Width (ft)
Existing Design	0
Proposed Design	2
Design Standard	4

It was determined that a relative comparison of CMFs would be an appropriate method for quantifying the safety impacts of the design exception because the required inputs and expertise to apply more rigorous methods were not available to the designer. Applicable CMFs were identified from the HSM (5). The following table presents the CMFs for each scenario along with the baseline conditions and applicability. [Note that all CMFs apply to total crashes on rural, two-lane roads and all are relative to the same baseline condition (6-ft shoulders).]

Scenario	CMF	Baseline Condition	Applicable Facility Type	Applicable Crash Type	Applicable Crash Severity
Existing Design (0-ft shoulders)	1.29	6-ft shoulders	Rural two-lane	All	All
Proposed Design (2-ft shoulders)	1.17	6-ft shoulders	Rural two-lane	All	All
Design Standard (4-ft shoulders)	1.09	6-ft shoulders	Rural two-lane	All	All

There are three conditions to be compared in this example: 1) 0-ft shoulders (existing), 2) 2-ft shoulders (proposed), and 3) 4-ft shoulders (design standard). If the applicable CMFs are relative to the same baseline, which they are in this example, then the ratio of any two CMFs can be used to estimate the relative safety impact between the two conditions. For example, the safety impact of the proposed design (CMF = 1.17) compared to the existing design (CMF = 1.29) is estimated by taking the ratio of the respective CMFs (1.17/1.29 = 0.91). Based on this comparison, it is anticipated that crashes will be reduced by nine percent (100(1-0.91)) by adding 2-ft shoulders to an existing rural two-lane road with no shoulders. The following table summarizes the safety impacts for various combinations of scenario comparisons.*

Comparison		Applicable CMFs		Safety Impact of Scenario A Relative to Scenario B
Scenario A	Scenario B	Scenario A	Scenario B	
2-ft shoulders	0-ft shoulders	1.17	1.29	0.91 (9% reduction)
4-ft shoulders	0-ft shoulders	1.09	1.29	0.84 (16% reduction)
2-ft shoulders	4-ft shoulders	1.17	1.09	1.07 (7% increase)

While the proposed design exception (2-ft shoulders) does not provide the estimated level of safety associated with the design standard (4-ft shoulders), it does provide a safety benefit compared to the existing conditions (0-ft shoulders). Specifically, the proposed 2-ft shoulders are anticipated to reduce crashes by nine percent compared

to existing conditions; an additional seven percent reduction in crashes would be anticipated if 4-ft shoulders are provided. The next step will be to determine whether or not the additional reduction in crashes is feasible after comparing the alternatives in terms of cost and other factors such as operational and environmental impacts.

This represents a quantitative safety analysis and provides more specific information than simply indicating that crashes are likely to increase as shoulder width decreases. The safety analysis, however, is only one aspect of the proposed design exception. In addition, the cost, operational, and environmental impacts of the various alternatives should be considered as well as potential mitigation measures.

If the applicable CMFs are not relative to the same baseline, then one additional step is necessary in the previous example to create a common baseline for the applicable CMFs before proceeding with the comparison. The same general rule is applied, taking the ratio of CMFs to estimate the impact of Scenario A relative to Scenario B, but Scenario B would be the same for all ratios before proceeding to compare other scenarios. This case is rare but could apply if the applicable range of CMFs differs for two studies and the roadway conditions in question are not covered by a single study. For example, it would not be possible to use a single study for the scenario above if one study developed CMFs for shoulder widths of zero to two feet and another study developed CMFs for shoulder widths of two to six feet.

Estimating the Safety Impacts of Design Decisions 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 design values for a given design element. 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 (12)*.

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.

Example: Continuing with the previous example, suppose now that the designer would like to determine if it is cost-effective (i.e., benefit-cost ratio greater than 1.0) to increase the shoulder width beyond the existing width and, if so, is it cost-effective to provide the minimum design standard (4-ft shoulders). This analysis requires an estimate of the benefit and cost of each scenario 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 scenarios compared to the existing conditions. [Note that these costs would be based on average construction costs provided by the State or local agency.]

Scenario	Construction Cost (per mile)	Annual Operating and Maintenance Cost	Service Life
Proposed Design (2-ft shoulders)	$200,000	Negligible	12
Design Standard (4-ft shoulders)	$500,000	Negligible	12

The five-year average crash frequency for the existing rural two-lane road is 7.2 crashes per mile per year. This is used as the estimate of crashes without treatment (i.e., existing 0-ft shoulders). [Note that more rigorous methods should be used to estimate crashes without treatment when the required inputs are available.]

Recall that the CMFs for constructing 2-ft shoulders and 4-ft shoulders, relative to the existing 0-ft shoulders are 0.91 and 0.84, respectively. The CMFs are applied individually to estimate the crashes for each scenario as follows:

Estimated crashes with treatment = CMF * Estimated crashes without treatment

Proposed Design Exception (2-ft shoulders):

Estimated crashes = 0.91 * 7.2 crashes per mile per year = 6.5 crashes/mile-year

Design Standard (4-ft shoulders):

Estimated crashes = 0.84 * 7.2 crashes per mile per year = 6.1 crashes/mile-year

The estimated change in crashes per mile-year is calculated as the estimated crashes under existing conditions minus the estimated crashes for the design condition of interest. For the proposed design exception (2-ft shoulders), the estimated change in crashes is 0.7 crashes per mile-year (7.2 crashes per mile-year minus 6.5 crashes per mile-year). For the design standard (4-ft shoulders), the estimated change in crashes is 1.1 crashes per mile-year (7.2 crashes per mile-year minus 6.1 crashes per mile-year).

The dollar value of the annual safety benefit is then computed by multiplying the change in crashes per mile-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 (13). The HSM (5) 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 (13). 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 (13). [Note that crash costs vary by type and severity and different costs would apply if the analysis was based on different crash types or severities. If possible, the analyst should use local crash costs by severity level.] For the proposed design exception (2-ft shoulders), the annual benefit is $21,591 (0.7 crashes per mile-year times $32,236 per crash) compared to the existing condition. For the design standard (4-ft shoulders), the annual benefit is $35,984 (1.1 crashes per mile-year times $32,236 per crash) compared to the existing condition.

The present value is computed for each scenario using the following equation. This example assumes an inflation rate of three percent, and a service life of 12 years for both scenarios. 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 the proposed design exception is computed as follows:

$$\text{Present Value of Proposed Design Exception} = \$21,591 * \frac{(1 + 0.03)^{12} - 1}{0.03 * (1 + 0.03)^{12}} = \$214,913$$

The present value of the safety benefits of the design standard is computed as follows:

$$\text{Present Value of Design Standard} = \$35{,}984 * \frac{(1 + 0.03)^{12} - 1}{0.03 * (1 + 0.03)^{12}} = \$358{,}189$$

The benefit-cost ratio is computed as the present value of the benefits divided by the present value of the total project costs. For the proposed design exception, the benefit-cost ratio is 1.1 ($214,913 / $200,000). For the design standard, the benefit-cost ratio is 0.7 ($358,189 / $500,000). From this analysis, it is shown that only the proposed design exception is economically justified (benefit-cost ratio greater than 1.0) and is also more cost-effective (i.e., greater improvement per dollar spent) than the design standard.

Assessment of Mitigation Measures

Similar to quantifying the impacts of design decisions and exceptions on the safety performance of a facility, these methods can be used to estimate the safety impact of implementing mitigation measures. The procedure is identical to those described in the previous applications, but the level of effort required for the analysis depends on the desired output. If it is sufficient to compare the estimated percent reduction in crashes, then the *Relative Comparison of CMFs* is employed. If it is desired to estimate the number of crashes after implementing the mitigation measure, then it would be necessary to employ a more rigorous method such as *Expected Crash Frequency with CMF Adjustment*. Other methods such as *Observed Crash Frequency with CMF Adjustment* or *Predicted Crash Frequency with CMF Adjustment* could also be used depending on the situation. For help selecting an appropriate method, refer to the section titled: *Selecting an Appropriate Method*.

CASE STUDIES

CMFs can be applied to quantify the safety impacts of design elements and estimate the effects of mitigation measures. Combined, these results can be used to evaluate the overall impacts of a design exception on the estimated safety performance of a facility. The following case studies illustrate how CMFs have been applied by the California Department of Transportation (Caltrans) and the Missouri Department of Transportation (MoDOT) in the design process.

Case Study #1: Evaluating Design Exceptions 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 individual design elements and evaluate the overall impact of design exceptions on the safety performance of a facility. Information for the case study was provided by Caltrans.

Project Description

In response to 24 collisions that occurred in a three-year period within a section of US 199 in Northern California, District 1 of Caltrans proposed a series of engineering improvements

to address potential safety issues. The project limits are within United States Forest Service Lands in Del Norte County, approximately two miles north of Hiouchi. The limits extend from 0.9 to 1.1 miles north of South Fork Road. The existing alignment consists of two curves with a short tangent transition, forming a reverse curve. Curve 2 was the primary focus of the engineering improvements as all 24 crashes occurred along this curve during the three-year period. The study location is characterized by the following variables and circled in Figure 1.

- Area type: rural.
- Terrain: mountainous.
- Number of lanes: two-lane road.
- Annual average daily traffic (AADT):
  - Year 2010: 4,300 vehicles per day.
  - Year 2016 (construction year): 4,560 vehicles per day.
- Posted speed: 55 mph (also the design speed).
- Horizontal curvature:
  - Curve 1: 750 ft radius.
  - Curve 2: 300 ft radius.
- Lane width: 11 ft.
- Shoulder width: 0 – 2 ft.

Documentation of Design Exceptions

Design exceptions were proposed for design elements related to the superelevation runoff length, superelevation runoff transition, and alignment consistency *(14)*. Further discussion of each of these elements is provided below.

<u>Superelevation Runoff Length</u>

The Caltrans Highway Design Manual indicates that "when horizontal curves reverse, the connecting tangents should be long enough to accommodate the standard superelevation runoffs." For this project, Caltrans proposed to increase the existing runoff length, but the proposed length was still less than standard. As further justification for the proposed design exception, it was noted that the proposed runoff lengths are similar to those at adjacent sections of US 199 and, as such, are not anticipated to violate driver expectation.

Figure 1: Project Location *(14)*

<u>Superelevation Runoff Transition</u>

The Caltrans Highway Design Manual specifies that "two-thirds of the superelevation runoff should be on the tangent and one-third within the curve." In order to meet this standard, the length of the tangent section would need to be increased.

<u>Alignment Consistency</u>

The Caltrans Highway Design Manual indicates that "where physical restrictions on curve radius cannot be overcome and it becomes necessary to introduce curvature of lower standard than the design speed of the project, the design speed between successive curves should change not more than 10 mph. Introduction of curves with lower design speeds should be avoided at the end of long tangents, steep downgrades, or at other locations where high approach speeds may be anticipated". In order to meet the standard, the radius of Curve 2 would need to be increased from 300 feet to 700 feet. For this project, Caltrans proposed to increase the radius of Curve 2 from 300 feet to 400 feet.
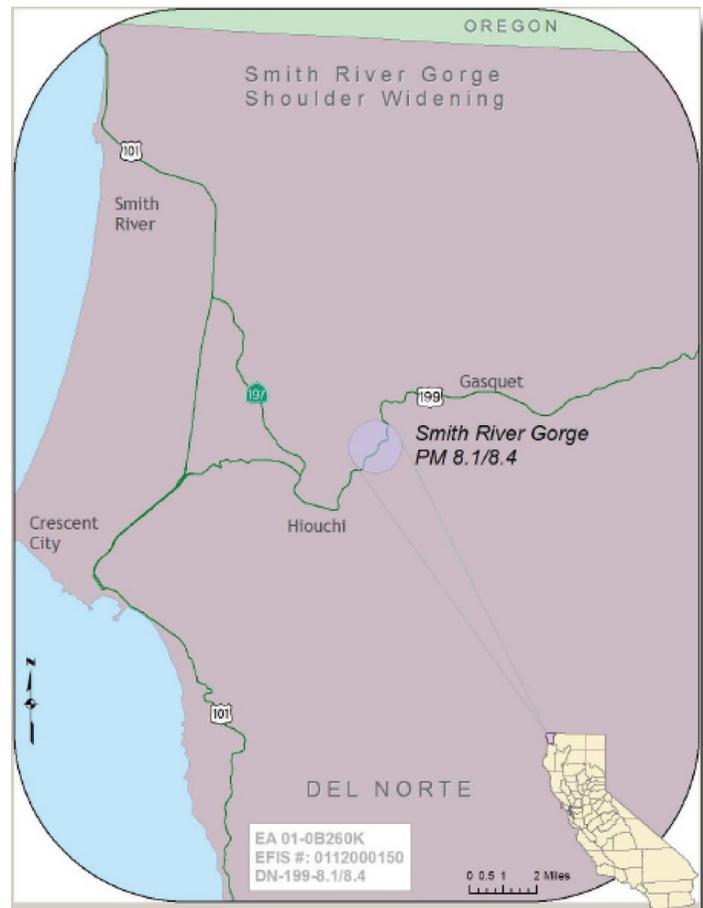
<u>Summary of Other Factors</u>

The following were documented as requirements to meet the standard runoff length, runoff transition, and alignment consistency:
- Excavation of 50-ft tall rock slopes to accommodate realignment.
- Additional and taller retaining walls.
- Additional fill due to increasing the wall height.
- Additional drainage work.

In addition, the historical Cold Springs Mountain Trail, located adjacent to this segment of US 199, would also have to be realigned to accommodate the larger radii. This would result in excessive costs due to the significant impacts to the right-of-way and environment.

The documentation of the design exception explains the effort required to comply with the Caltrans Highway Design Manual, proposes exceptions to specific design elements, and identifies measures to mitigate the potential safety impacts of exceptions to the Caltrans Highway Design Manual. It was anticipated that curve-related crashes would be reduced by increasing the radius of Curve 2, but not to the extent that they could be reduced by increasing the radius to meet the applicable design criteria. To further enhance safety on Curve 2, mitigation measures were proposed, including increasing the superelevation, lane width, and shoulder width within the sub-standard section. These mitigation measures are expected to further reduce curve-related crashes, particularly single-vehicle roadway departures. CMFs were applied to demonstrate the safety benefit of the proposed design exceptions and mitigation measures compared to the existing conditions. The application of CMFs is detailed in the following section, *Practical Application of CMFs*.

Practical Application of CMFs

The following CMFs and computations are associated with Curve 2 since this was the focus of the engineering improvements, design exception requests, and safety analysis. Recall that all 24 crashes occurred within Curve 2 during the three-year study period. The existing and proposed conditions are summarized in Table 1.

Table 1. Summary of Existing and Proposed Conditions

Feature	Existing	Proposed
Curve 2 Radius (ft)	300	400
Curve 2 Length (mi)	0.0536	0.0536
Superelevation	0.072	0.120
Lane Width (ft)	11	12
Shoulder Width (ft)	0 - 2	8

In addition to these improvements, Caltrans proposed to increase the runoff lengths and install shoulder rumble strips. However, CMFs are currently not listed in the HSM for these improvements and thus were not used in the calculations.

Table 2 identifies the CMFs associated with the existing and proposed conditions as well as their applicability and baseline conditions. Note that all CMFs apply to all crashes

Note that while CMFs were used to compare the estimated safety impacts of the proposed design exceptions with respect to the existing conditions, it is also desirable to compare the estimated safety impacts of the proposed design exceptions with respect to the design standards.

Note that while Caltrans only used CMFs from the HSM *(5)*, the CMF Clearinghouse *(7)* is another source of CMFs. For example, CMFs for shoulder rumble strips are available in the CMF Clearinghouse.

on rural, two-lane curves. From the HSM *(5)*, the following equation is used to estimate the CMF for a given curve radius compared to a tangent section.

$$CMF_{curve} = \frac{1.55L_c + \frac{80.2}{R} - 0.012S}{1.55L_c}$$

Where:
CMF_{curve} = CMF for the effect of horizontal alignment on total crashes compared to a tangent section.
L_c = length of horizontal curve (miles) which includes spiral transitions, if present.
R = radius of curvature (feet).
S = 1 if spiral transition curve is present; 0 if spiral transition curve is not present; 0.5 if a spiral transition curve is present at one but not both ends of the horizontal curve.

From the HSM *(5)*, the following equations are used to estimate the CMF for the superelevation variance of a horizontal curve (i.e., the difference between the actual superelevation and the superelevation identified by AASHTO policy). When the actual superelevation meets or exceeds that in the AASHTO policy, or when the superelevation variance is less than 0.01, the value of the superelevation CMF is 1.00.

CMF_{SV} = 1 + 6(SV - 0.01) for 0.01 ≤ SV < 0.02

CMF_{SV} = 1.06 + 3(SV - 0.02) for SV ≥ 0.02

Where:
CMF_{SV} = CMF for the effect of superelevation variance on total crashes.
SV = superelevation variance (ft/ft), which represents the superelevation rate contained in the AASHTO Green Book minus the actual superelevation of the curve.

From the HSM *(5)*, the CMFs for 11-ft lanes and 12-ft lanes are 1.05 and 1.00, respectively. The CMFs for 0-ft shoulders, 2-ft shoulders, and 8-ft shoulders are 1.50, 1.30, and 0.87. Note that the CMFs for lane and shoulder width apply to run-off-road, head-on, and sideswipe crashes. Using the following equation from the HSM, the CMFs are adjusted to estimate the impact on total crashes. A slightly different equation is used when the shoulder type changes.

CMF_{total} = ($CMF_{related}$ - 1.0) $*$ P_r + 1.0

Where:
CMF_{total} = CMF for total crashes.
$CMF_{related}$ = CMF for related crashes (i.e., run-off-road, head-on, and sideswipe crashes).
P_r = proportion of total crashes constituted by related crashes (default = 0.574).

Table 2. Summary of CMFs for Existing and Proposed Conditions

Feature	CMF	Baseline Condition	Applicability
Existing Radius (300 ft)	4.23	Tangent	All crashes on rural, two-lane curves
Proposed Radius (400 ft)	3.42	Tangent	All crashes on rural, two-lane curves
Existing Superelevation (0.07)	1.14	0.12	All crashes on rural, two-lane curves
Proposed Superelevation (0.12)	1.00	0.12	All crashes on rural, two-lane curves
Existing Lane Width (11 ft)	1.03	12-ft	All crashes on rural, two-lane roads
Proposed Lane Width (12 ft)	1.00	12-ft	All crashes on rural, two-lane roads
Existing Shoulder Width (0 ft)	1.29	6-ft	All crashes on rural, two-lane roads
Existing Shoulder Width (2 ft)	1.17	6-ft	All crashes on rural, two-lane roads
Proposed Shoulder Width (8 ft)	0.93	6-ft	All crashes on rural, two-lane roads

The safety impact of the proposed design compared to the existing design is estimated by taking the ratio of the respective CMFs (CMF for proposed design divided by CMF for existing design). Table 3 summarizes the safety impacts for the scenarios of interest. Since the existing shoulder width varied between zero and two feet, Caltrans took the average of the CMFs for the two conditions to represent the CMF for the existing condition. Hence, a CMF of 1.23 (average of 1.17 and 1.29) was used to represent the CMF for the existing shoulder width.

Table 3. Summary of CMFs and Estimated Safety Impacts

Feature	Proposed Condition	Existing Condition	CMF (Proposed)	CMF (Existing)	Safety Impact of Proposed Relative to Existing Design
Radius	400 ft	300 ft	3.42	4.23	0.81 (19% reduction)
Superelevation	0.120	0.072	1.00	1.14	0.88 (12% reduction)
Lane Width	12 ft	11 ft	1.00	1.03	0.97 (3% reduction)
Shoulder Width	8 ft	0-2 ft	0.93	1.23	0.76 (24% reduction)

Note that CMFs should only be multiplied if they apply to the same crash types and severities and the HSM urges caution in multiplying more than three CMFs.

Note that Caltrans multiplied four CMFs whereas the HSM urges caution in multiplying more than three CMFs.

The CMFs were then combined to estimate the overall safety impact of the proposed design exception and mitigation measures compared to the existing conditions. As recommended in the HSM *(5)*, the CMFs were multiplied to estimate the cumulative effect of the combined treatments.

In this case, all 24 observed crashes within Curve 2 are considered as "total crashes" since the study section includes the curve only. As such, the CMFs in Table 2 apply to the same crash types and severities. Therefore, it was acceptable to multiply the CMFs to estimate the combined safety impact.

The following shows the calculation and resulting CMF for the estimated combined effect.

Combined CMF = 0.81 * 0.88 * 0.97 * 0.76 = 0.53

The three-year observed crash history (24 crashes) was used to estimate the annual crashes without treatment (i.e., no changes to existing conditions) as shown in the following calculation.

Estimated Annual Crashes without Treatment = 24 crashes / 3 years = 8.0 crashes/year

The combined CMF can then be applied to the estimated annual crashes without treatment to estimate the annual crashes with treatment (i.e., proposed design) as shown in the following calculation.

Estimated Annual Crashes with Treatment = 0.53 * 8.0 crashes/year = 4.24 crashes/year

Based on the above calculations, the proposed design exception and mitigation measures are anticipated to perform better than the existing conditions. Specifically, the proposed design is anticipated to reduce crashes by 3.8 crashes per year (8.0 crashes per year minus 4.24 crashes per year). While the proposed design is anticipated to improve safety compared to the existing conditions, the design standard would provide a higher level of safety. In the future, the same process can be used to estimate the safety performance of the design

standard. The safety performance of the proposed design can then be compared to the existing conditions and design standard. The estimated safety impacts can then be considered in conjunction with other factors such as project cost, operational performance, and environmental impacts.

For more information about the case study, please contact Thomas M. Schriber, Caltrans; Traffic Liaison & Reviewer; 916-654-7138; thomas_schriber@dot.ca.gov.

Summary of Findings

CMFs can be applied to quantify the safety impacts of design elements and estimate the effects of mitigation measures. Combined, these results can be used to evaluate the overall impacts of design exceptions on the estimated safety performance of a facility. In this case, District 1 of Caltrans used CMFs in order to quantify the safety impacts of increasing the radius of a curve, increasing the superelevation, increasing the width of the travel lane, and increasing the shoulder width. Even though some of the proposed changes did not meet the design standard based on California's design documents, the use of CMFs demonstrated that the proposed improvements could result in a substantial reduction in crashes compared to the existing conditions. Further analysis could compare the estimated safety impact of proposed design exceptions with respect to design standards. The results of the safety analysis could also be considered in conjunction with other factors such as project cost, operational performance, and environmental impacts.

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

The following case study illustrates how the *Predicted Crash Frequency with CMF Adjustment* method has been used to assess the safety impact of individual design elements and evaluate the overall impact of design exceptions on the safety performance of a facility. Information for the case study was provided by the Missouri Department of Transportation (MoDOT).

MoDOT integrates data-driven decision-making in many of their planning and design practices, including the design exception process. To promote data-driven decision-making, MoDOT established a policy to conduct a safety analysis as part of the evaluation of design exceptions when the design exception "involves safety related features that are adequately addressed in the AASHTO Highway Safety Manual." Examples of safety related features identified in the MoDOT policy include lane width, shoulder width, shoulder type, rumble strips, turn lanes, bridge width, bridge approach rail, horizontal alignment, vertical alignment, grade, horizontal clearance, vertical clearance, and guardrail, but not all of these features are adequately addressed in the HSM. MoDOT also notes that this list is not inclusive and "any other items that may be perceived as a safety concern will also follow these requirements."

Project Description

MoDOT Central District proposed a project on a rural, two-lane section of Route 42 in Kaiser, MO. The existing conditions included a narrow cross-section with lane widths of 10.5 feet and unpaved shoulders. The proposed conditions included paved shoulders (2 feet in both directions) and shoulder and centerline rumble stripes. The design guidelines for minor roads in Missouri identify minimum expectations for several design features, including a consistent shoulder width of 2 to 4 feet. In this case, the District conducted an analysis, using Part C Predictive Methods of the HSM, to document the potential safety benefits of the proposed conditions compared to the existing conditions. A separate analysis is also provided to compare the safety performance of different shoulder widths (2 feet versus 4 feet). The existing (1-ft turf shoulders), proposed (2-ft paved shoulders), and alternative conditions (4-ft paved shoulders) for Route 42 are summarized in Table 4. The baseline conditions from the HSM are also provided in Table 4 *(5)*.

Table 4. Summary of Roadway Characteristics and Baseline Conditions

Roadway Characteristics	Existing[1]	Proposed[1]	Alternative[1]	Baseline[2]
Traffic volume	4,250	4,250	4,250	0 – 17,800
Length (mi)[3]	1.0	1.0	1.0	Not specified
Lane width (ft)	10.5	10.5	10.5	12
Shoulder width (ft)	1	2	4	6
Shoulder type	Turf	Paved	Paved	Paved
Horizontal curve length (mi)	0	0	0	0
Radius of curvature (ft)	0	0	0	0
Spiral transition curve (yes/no)	No	No	No	No
Superelevation variance (ft/ft)	0	0	0	0
Grade (%)	0	0	0	0
Driveway density (driveways/mi)	5	5	5	5
Centerline rumble stripes (yes/no)	No	Yes	Yes	No
Shoulder rumble stripes (yes/no)	No	Yes	Yes	Not applicable
Passing lanes (1 lane / 2 lanes / no)	No	No	No	No
Two-way left-turn lane (yes/no)	No	No	No	No
Roadside hazard rating (1-7 scale)	4	4	4	3
Segment lighting (yes/no)	No	No	No	No
Auto speed enforcement (yes/no)	No	No	No	No

Notes:
1. The purpose of the analysis was to estimate the relative change in safety for the three scenarios. While some of the elements listed in the table are present along the corridor (e.g., horizontal curvature and vertical grade), there is no change in the relative conditions for these elements among the three scenarios. As such, the values are assumed to be zero. Intersections were not included in the analysis for a similar reason.
2. The baseline conditions represent those associated with the HSM Part C Predictive Method for Rural Two-Lane Roads.
3. The study section is longer than one mile, but a one-mile section was assumed for the analysis. This was acceptable because the purpose of the analysis was to estimate the relative change in safety for the three scenarios, and the segment length remained constant among the three scenarios. As such, the results are presented in crashes per mile per year.

Practical Application of Predicted Crash Frequency with CMF Adjustment

For this analysis, MoDOT utilized the predictive method for two-lane rural roads from Part C of the HSM. Using the predictive method, a user specifies an applicable 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 4 *(5)*.

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

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 4,250 vehicles per day and a segment length of 1.0 mile, the predicted total crash frequency for the baseline conditions is computed as follows:

$$N_{SPF} = 4{,}250 * 1.0 * 365 * 10^{-6} * e^{-0.312}$$

$$N_{SPF} = 1.14 \text{ crashes per year}$$

CMFs were then identified to reflect the conditions of interest. The HSM Part C Predictive Method for Rural Two-Lane Roads provides specific CMFs for use with the SPF from Equation {1}. The CMFs are provided in Table 5 (5).

Table 5. Summary of CMFs for Conditions of Interest

Roadway Characteristics	Existing	Proposed	Alternative
Lane width	1.10	1.10	1.10
Shoulder width and type	1.24	1.17	1.09
Horizontal curves	1.00	1.00	1.00
Super-elevation	1.00	1.00	1.00
Grades	1.00	1.00	1.00
Driveway density	1.00	1.00	1.00
Centerline rumble stripes	1.00	0.94	0.94
Shoulder rumble stripes	1.00*	0.87*	0.87*
Passing lanes	1.00	1.00	1.00
Two-way left-turn lane	1.00	1.00	1.00
Roadside design	1.07	1.07	1.07
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 stripes. Instead, MoDOT obtained the CMF from workshop materials prepared by FHWA (15) and used the CMF to reflect the expected safety impacts of the shoulder rumble stripes.

The CMFs were then combined to estimate the overall safety impact of the conditions of interest. As recommended in the HSM (5), the CMFs were multiplied using Equation {2} to estimate the cumulative effect of the combined treatments for each scenario.

$$CMF_{Combined} = CMF_1 * CMF_2 * ... * CMF_n \quad \{2\}$$

Where:
$CMF_{Combined}$ = Crash modification factor for combined set of roadway characteristics.
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 existing, proposed, and alternative conditions are 1.46, 1.13, and 1.05 respectively.

$$CMF_{Combined} (Existing) = 1.10*1.24*1.07*1.00^{10} = 1.46$$

$$CMF_{Combined} (Proposed) = 1.10*1.17*0.94*0.87*1.07*1.00^8 = 1.13$$

$$CMF_{Combined} (Desired) = 1.10*1.09*0.94*0.87*1.07*1.00^8 = 1.05$$

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.

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.

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

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 6. Note that the baseline predicted crashes are identical for the three scenarios.

$$N_{Predicted} \text{ (Existing)} = 1.14 * 1.46 = 1.66$$

$$N_{Predicted} \text{ (Proposed)} = 1.14 * 1.13 = 1.29$$

$$N_{Predicted} \text{ (Desired)} = 1.14 * 1.05 = 1.20$$

Table 6. Summary of Computations for Predicted Annual Crashes per Mile

Scenario	N_{SPF} Equation {1}	$CMF_{Combined}$ Equation {2}	$N_{Predicted}$ Equation {3}	Percent Reduction (Compared to Existing)
Existing	1.14	1.46	1.66	–
Proposed	1.14	1.13	1.29	22%
Alternative	1.14	1.05	1.20	28%

Note that the results reflect crashes per mile per year because the segment length was specified as one mile. Projected over a 10-year period or over a longer segment, the proposed and alternative design conditions will provide a notable reduction in crashes compared to the existing conditions. Recall that certain roadway characteristics (e.g., horizontal curvature, vertical grade, and intersections) were not included in the analysis because the related conditions did not change among the three scenarios. As such, the comparison of the relative safety impacts of the three scenarios is based on the percent change in crashes rather than the predicted number of crashes.

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, MoDOT had not developed a local calibration factor. As a result, a local calibration factor of 1.0 was assumed.

Note that calibrated SPFs provide more reliable results than non-calibrated SPFs for predicting crash frequency. As such, 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.

Based on the above calculations, the proposed design is predicted to perform better than the existing conditions with respect to safety. Specifically, the proposed design is predicted to reduce total crashes by 0.37 crashes per mile per year (1.66 crashes per year minus 1.29 crashes per mile per year). This represents a 22 percent reduction in predicted total crashes. The alternative scenario is predicted to provide a higher level of safety than both the existing and proposed conditions.

MoDOT employs Microsoft Excel spreadsheets to assist with the computations. The spreadsheets can be used to estimate predicted crashes when the observed crash history is not available or applicable. When the observed crash history is available and applicable, the spreadsheets can be used to estimate the expected crashes using the Empirical Bayes method. Similar spreadsheets are available at: www.highwaysafetymanual.org.

For more information about the case study, please contact Ashley Reinkemeyer; MoDOT; Senior Traffic Studies Specialist; 573-751-3728; Ashley.Reinkemeyer@modot.mo.gov.

Summary of Findings

SPFs can be used to predict crashes for baseline conditions and CMFs can be applied to adjust the baseline estimate to reflect specific conditions of interest. This is useful for quantifying and comparing the safety performance of scenarios with different design features and can aid in the decision-making process. Specifically, this approach can help an agency to better

understand the potential safety impacts of individual design elements and design exceptions. MoDOT conducts similar safety analyses as part of the evaluation of design exceptions that involve safety related features. In this case, Central District of MoDOT used the *Predicted Crash Frequency with CMF Adjustment* method in order to quantify the safety impacts of installing a paved shoulder with shoulder and centerline rumble stripes. Two different scenarios are compared to the existing conditions. The proposed condition included a paved shoulder width of two feet, while the alternative condition based on design guidelines is a paved shoulder width of four feet. The use of this quantitative method demonstrated that the proposed improvements could result in a substantial reduction in crashes compared to existing conditions. Recall that non-calibrated SPFs may overestimate or underestimate the predicted crash frequency, but provide a reasonable estimate of the percent difference in crashes among alternatives. As such, it is desirable to use a calibrated SPF if it is necessary to estimate the change in predicted crash frequency or conduct a formal economic analysis.

OVERCOMING POTENTIAL CHALLENGES

Potential challenges may arise when quantifying the safety impacts of design decisions. 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 performance for design decisions 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 design elements or mitigation measures. The CMF Clearinghouse *(7)* 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 design elements and treatments, including many of the 13 controlling criteria, combination treatments, and those treatments 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 safety effects of the 13 controlling criteria, including a reference to specific CMFs when available. CMFs are included in the HSM for five of the 13 design criteria for rural, two-lane roads and two design criteria for rural multilane roads. Other CMFs are available in the CMF Clearinghouse *(7)* and recently completed research studies such as NCHRP Project 17-45 *(9)*. Additional research is underway to develop CMFs for design criteria 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 *(7)* 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.

If a calibrated SPF is used to estimate the predicted crash frequency, then a formal cost-benefit analysis could be conducted to determine whether or not the additional shoulder width for the alternative scenario is worth the added project costs.

It is desirable to compare the estimated safety performance of the proposed conditions with respect to both the existing conditions and design standards.

It is possible to conduct additional analyses to predict the number of crashes by crash type and severity using Part C of the Highway Safety Manual.

Note that it may be possible to employ the Empirical Bayes method to increase the reliability of the results. The Empirical Bayes method combines the observed crash history for the location of interest with the predicted crashes from an applicable SPF. The Empirical Bayes method is preferred when observed crash data are available and applicable.

Design Criteria	Rural 2-Lane	Rural Multilane	Urban Arterial	Suburban Arterial	Freeway
Design Speed	–	–	–	–	–
Lane Width	CMF in HSM Section 13.4.2.1	CMF in HSM Section 13.4.2.1	–[1]	–[1]	–[2]
Shoulder Width	CMF in HSM Section 13.4.2.4	CMF in HSM Section 13.4.2.4	–	–	–[3]
Bridge Width	–[4]	–	–	–	–
Horizontal Alignment	CMF in HSM Section 13.6.2.1	–[5]	–	–	–[6]
Vertical Alignment	–	–	–	–	–
Grade	CMF in HSM Section 13.6.2.3	–	–	–	–
Stopping Sight Distance	–	–	–	–	–
Cross Slope	–	–	–	–	–
Superelevation	CMF in HSM Section 13.6.2.2	–	–	–	–
Horizontal Clearance / Lateral Offset	–[7]	–[7]	–[7]	–[7]	–[7]
Vertical Clearance	–	–	–	–	–
Structural Capacity	–	–	–	–	–

– Indicates that a CMF is not available in the current edition of the HSM.

[1] The HSM Chapter 12 (Predictive Method for Urban and Suburban Arterials) does not include a CMF for lane width on urban and suburban arterials. Recent research from NCHRP Project 3-72 found little to no difference in safety performance for urban and suburban arterials in the range of lane widths from 10 to 12 feet.

[2] The HSM currently does not include a CMF for lane width on freeways; however, NCHRP Project 17-45 has developed a proposed HSM safety prediction methodology for freeways that includes lane width.

[3] The HSM currently does not include a CMF for freeway shoulder widths; however, NCHRP Project 17-45 has developed a proposed HSM safety prediction methodology for freeways that includes width for right (outside) and left (inside) shoulders.

[4] The FHWA CMF Clearinghouse has some information and provides CMFs for changing bridge widths for certain roads and volumes.

[5] The HSM Chapter 11 (Rural Multilane Highways) does not include a CMF for horizontal curves. There are several CMFs for horizontal curve radius in the FHWA CMF Clearinghouse for certain roads and conditions.

[6] The HSM currently does not include a CMF for horizontal curves on freeways; however, NCHRP Project 17-45 has developed a proposed HSM safety prediction methodology for freeways that includes the safety effects of horizontal curves.

[7] The HSM does not contain CMFs for lateral offset. The CMFs for shoulder width in part reflect the safety effects of lateral offset.

Caltrans noted that CMFs were not available in the HSM for all proposed conditions in the design exception case study. While this is a limitation of existing research, FHWA's CMF Clearinghouse provides additional CMFs that may be considered for future safety analysis of design elements.

Applicability of CMFs

CMFs are developed based on a sample of sites with specific conditions. While a CMF may be available for a given design element, it may not be appropriate for the scenario of interest. For example, there may be significant differences between the characteristics of a study site and the sites used to develop the CMF (e.g., different area type, number of lanes, or traffic volume). The HSM (5) and CMF Clearinghouse (7) provide information to help users identify the applicability of CMFs.

A related challenge may be that multiple CMFs exist for the same design element and conditions. This is particularly challenging when multiple studies have estimated CMFs

for the same feature 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 situations 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 *(7)* under FAQs.

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 *(5)* and posted on the CMF Clearinghouse *(7)*. 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 *(10, 11)*.

Insufficient Expertise

A specific challenge for the design engineer could be that they have insufficient expertise 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., design decisions and exceptions), 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 design engineer 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 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).

Caltrans indicated that CMFs were used to estimate the safety impacts of design elements. The results of the analysis were included in the documentation of the design exception, but were not directly used in the decision making process. Instead, Caltrans used the results as a 'point of discussion'. Part of the reason was that for District 1, this was the first application of CMFs in the design exception process, and the design team was not comfortable with the use of the results due to their lack of familiarity. This will hopefully change in the future as agencies continue to adopt the procedures in the HSM and incorporate CMFs in the project development process, particularly in estimating the safety impacts of design elements.

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

District 1 of Caltrans did not have access to applicable SPFs. As such, the number of observed crashes (three-year history) was used to estimate the crashes without treatment. The estimated treatment effect is a function of the CMFs and is applicable regardless of whether or not SPFs are used to estimate the crashes without treatment. SPFs, particularly in combination with the observed crash history, offer a more rigorous method to estimate the crashes without treatment.

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 of this guide 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 *(5)* and related documentation, *Integrating the HSM into the Highway Project Development Process (6)*.

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CMF

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