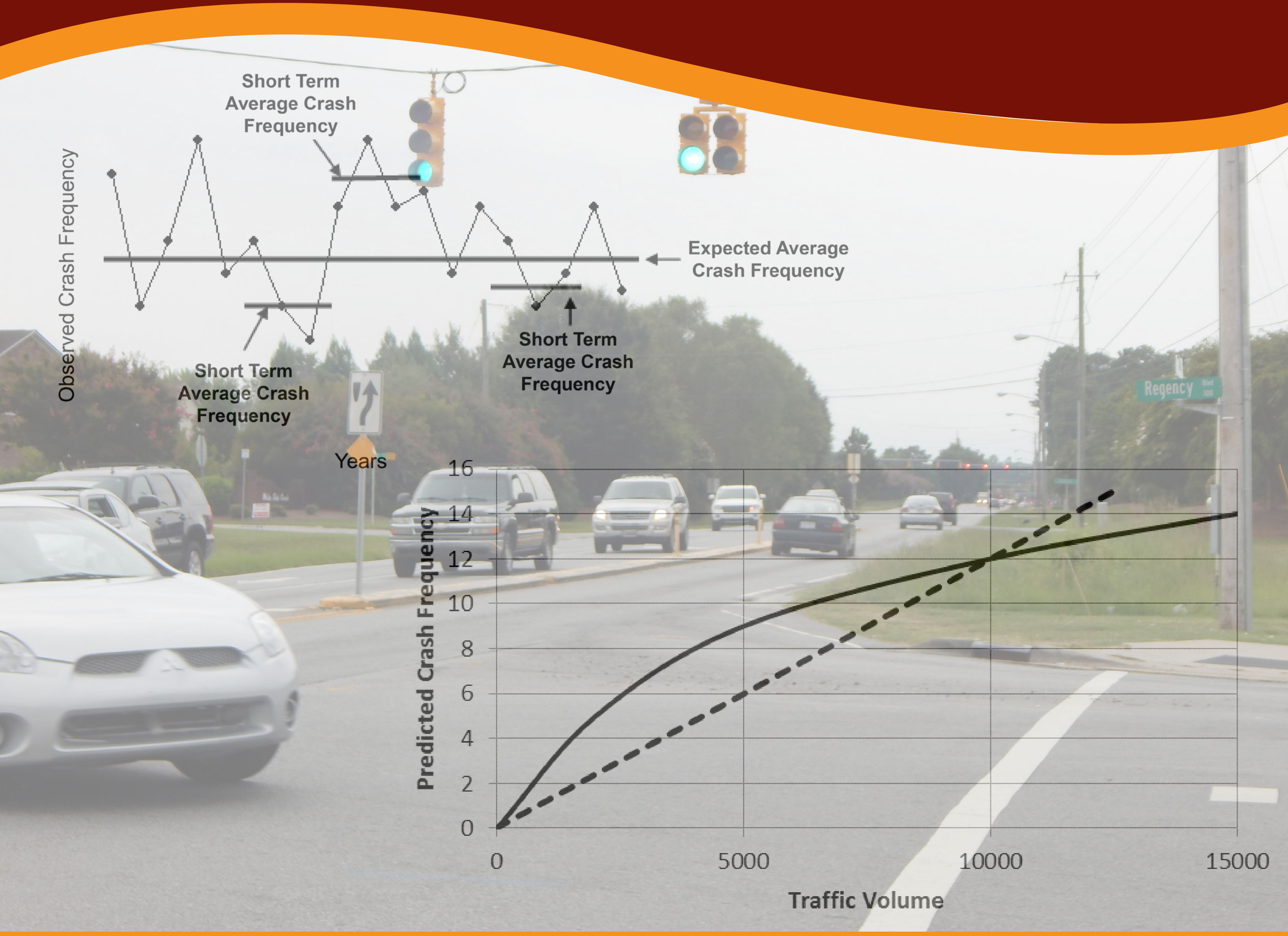
Reliability of Safety Management Methods

Countermeasure Selection



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16. Abstract

High quality data and reliable analytical methods are the foundation of data-driven decision-making. The Reliability of Safety Management Methods series includes five information guides that identify opportunities to employ state-of-the-art (more reliable) methods to support decisions throughout the roadway safety management process. Four of the guides focus on specific components of the Roadway Safety Management process: network screening, diagnosis, countermeasure selection, and safety effectiveness evaluation. The fifth guide focuses on the systemic approach to safety management, which describes a complimentary approach to the methods described in the network screening, diagnosis, and countermeasure selection guides. The purpose of the Reliability of Safety Management Methods series is to demonstrate the value of more reliable methods in these activities, and demonstrate limitations of traditional (less reliable) methods.

The Reliability of Safety Management Methods: Countermeasure Selection information guide describes various methods and the latest tools to support countermeasure selection. The target audience includes data analysts, project managers, and program managers involved in projects that impact highway safety. The objectives of this information guide are to 1) raise awareness of more reliable methods, and 2) demonstrate through examples the value of more reliable methods in countermeasure selection. This information guide compares more reliable countermeasure selection methods to traditional methods which are more susceptible to bias and may result in less reliable estimates and less effective decisions. Readers will understand the value of and be prepared to select more reliable methods in countermeasure selection.

The remainder of this information guide includes five sections. The first section introduces the roadway safety management process and countermeasure selection. The second section provides an overview of various methods related to countermeasure selection. The third section demonstrates the value of more reliable methods compared to traditional methods for selecting countermeasures. Examples highlight the shortcomings of less reliable methods, which may lead to misinformed decisions, non-optimum use of funds, and the implementation of less effective treatments. The fourth section summarizes the data requirements to employ the various methods. The final section describes available tools and resources to support countermeasure selection.

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Office of Safety Technical Working Group

Stuart Thompson, FHWA Office of Safety

Ray Krammes, FHWA Office of Safety

Yanira Rivera, FHWA Office of Safety

Karen Scurry, FHWA Office of Safety

Roya Amjadi, FHWA Office of Safety Research and Development

Craig Thor, FHWA Office of Safety Research and Development

Shawn Troy, North Carolina Department of Transportation

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LIST OF ACRONYMS

AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
CMF	Crash Modification Factor
EB	Empirical Bayes
F+I	Fatal plus injury
FHWA	Federal Highway Administration
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
PDO	Property damage only
QRS	Quality rating score
SPF	Safety Performance Function
SVROR	Single-vehicle run-off-road

PREFACE

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1. INTRODUCTION TO COUNTERMEASURE SELECTION

The roadway safety management process is a six-step process as shown in Figure 1 and outlined in the Highway Safety Manual.(1) The objectives of this process are as follows.

1. **Network Screening**: Identify locations that could benefit from treatments to improve safety performance (i.e., reduce crash frequency and severity). Refer to the Reliability of Safety Management Methods: Network Screening for further discussion of network screening and related methods.
2. **Diagnosis**: Understand collision patterns and crash contributing factors. Agencies identify crash trends and patterns based on past reported crashes, assess the crash types and severity levels, and study other elements that characterize the crashes, the environment, the behaviors of drivers and other road users, the emergency services, and infrastructure elements such as road geometry and traffic control devices. The result of diagnosis is a list of contributing factors associated with historical and potential future crashes. Refer to the Reliability of Safety Management Methods: Diagnosis for further discussion of diagnosis and related methods.
3. **Countermeasure Selection**: Identify, assess and select appropriate countermeasures to target crash contributing factors and reduce crash frequency and severity at identified locations. The countermeasures should directly target the crash contributing factors, and may include engineering, education, enforcement, and EMS-related measures (i.e., the 4E approach). Refer to the next sections of this information guide for further information and considerations related to countermeasure selection.
4. **Economic Appraisal**: Estimate the economic benefit and cost associated with a particular countermeasure or set of countermeasures. There is not a separate guide for economic appraisal in the Reliability of Safety Management Methods series because it involves policy-level decisions such as appropriate crash costs, discount rates, selected economic method, and non-monetary local considerations. Refer to chapter 7 of the Highway Safety Manual for further information and considerations related to economic appraisal.(1)
5. **Project Prioritization**: Develop a prioritized and optimal list of projects to improve the safety performance (i.e., reduce crash frequency and severity) of the road network, considering available resources. There is not a separate guide for project prioritization in the Reliability of Safety Management Methods series because it involves policy-level decisions such as overall agency goals. Refer to chapter 8 of the Highway Safety Manual for further information and considerations related to project prioritization.(1)
6. **Safety Effectiveness Evaluation**: Evaluate how a particular treatment (or group of treatments) has affected the safety performance (crash frequency and severity) of the treated locations and the system. Refer to the Reliability of Safety Management Methods: Safety Effectiveness Evaluation for further discussion of evaluation and related methods.

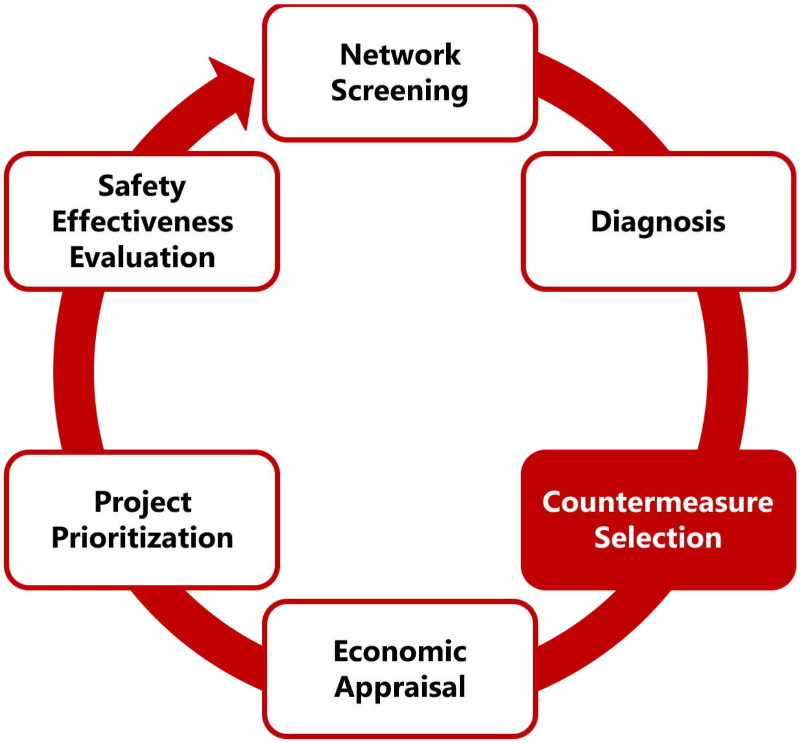


Figure 1. Diagram. Schematic of roadway safety management process.

The roadway safety management process is an integral part of the roadway infrastructure cycle and project development process. While the six-step roadway safety management process focuses on safety performance, it provides information for system planning, project planning, design and construction, and operations and maintenance of a transportation system. Figure 2 illustrates the roadway safety management process and how it supports decision-making processes, policy-making, and practices throughout the life cycle of a roadway.

Countermeasure selection is the third step in the roadway safety management process. The objective of countermeasure selection is to identify potential countermeasures and select the most effective countermeasure(s) to address or mitigate the underlying safety issues identified in step 2 (diagnosis) at the specific site. The outcome of the fifth step (project prioritization) feeds into the project development process (i.e., system planning, project planning, project design and construction, and system operations and maintenance). The results enable decision-makers, planners, highway designers, and traffic engineers to consider safety-motivated projects in conjunction with resurfacing, rehabilitation, reconstruction, and expansion projects. Following implementation of a countermeasure or project, it is necessary to evaluate the safety effects. The sixth step of the roadway safety management process (safety effectiveness evaluation) develops evidence-based safety information to support future decisions. In some cases, this evaluation leads to a crash modification factor (CMF).

CMFs are fundamental in the roadway safety management process as well as in the project development process. Analysts can use CMFs to estimate the change in crashes associated with a given countermeasure. Step 4 of the safety management process (economic appraisal) relies on the estimate of the change in crashes to determine the cost effectiveness of a countermeasure. Analysts can also use CMFs to compare the safety performance of alternatives such as planning-level alternatives, individual design elements, and traffic control devices.

A CMF is a multiplicative factor that indicates the expected change in crashes associated with a countermeasure. If you implement a countermeasure with a CMF of 1.0, you would not expect a change in associated crashes at the particular location. If you implement a countermeasure with a CMF less than 1.0, you would expect a reduction in associated crashes at the particular location. If you implement a countermeasure with a CMF greater than 1.0, you would expect an increase in associated crashes at the particular location.

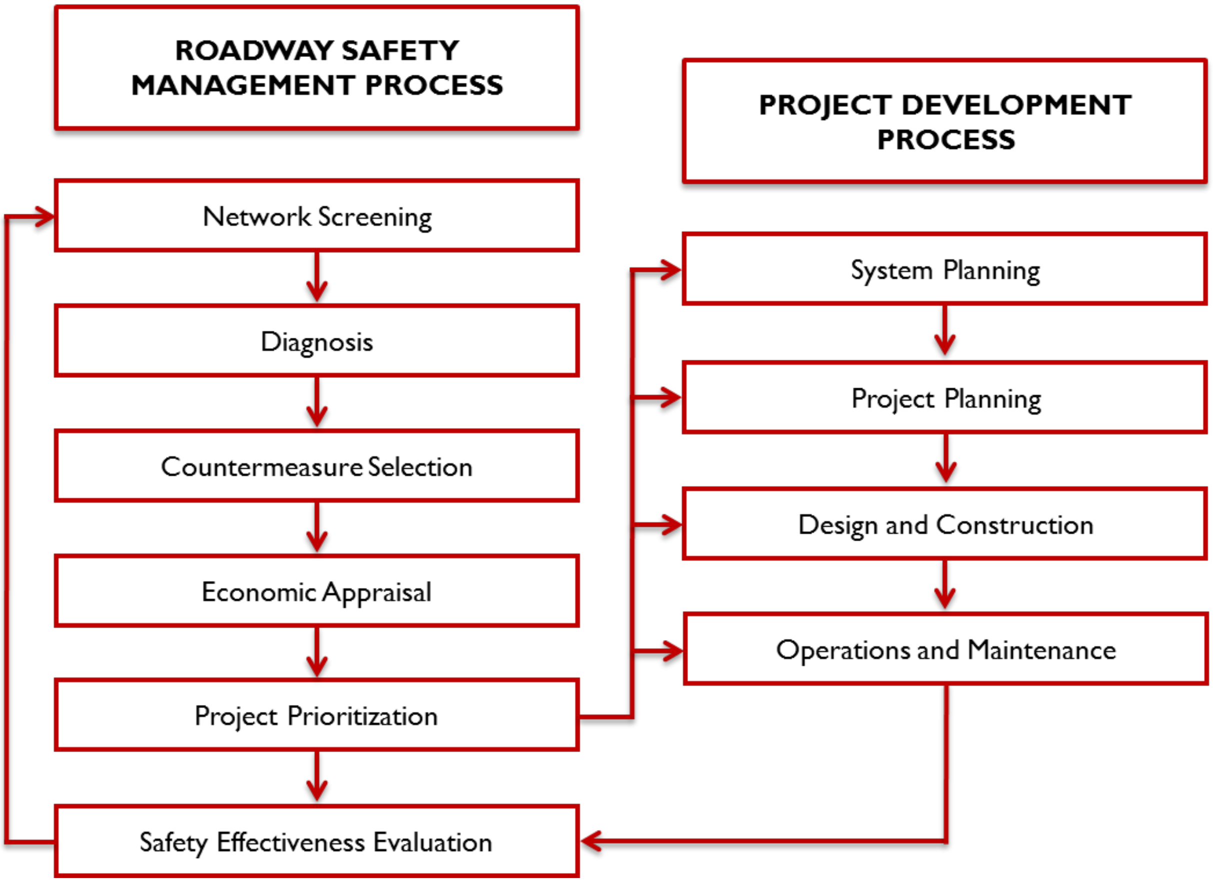


Figure 2. Diagram. Integrating the roadway safety management and project development process

2. OVERVIEW OF COUNTERMEASURE SELECTION METHODS

During step 3 of the roadway safety management process (countermeasure selection), analysts identify and assess potential countermeasures and select the most effective countermeasure(s) to address the contributing factors identified in step 2 (diagnosis). The first part of countermeasure selection is to develop countermeasures to target the underlying safety issues. Analysts can use tools such as the Haddon Matrix and resources such as the NCHRP Report 500 series to identify targeted countermeasures to address or mitigate underlying contributing factors.

The Haddon Matrix is a tool originally developed for injury prevention, but is directly applicable to highway safety in both diagnosis and countermeasure selection. (2) For diagnosis, the Haddon Matrix is useful to gain a comprehensive understanding of crash contributing factors. Analysts can use the Haddon Matrix to identify human, vehicle, and roadway factors contributing to the frequency and severity of crashes prior to, during, and after the crash event. Then, analysts can identify targeted reactive and proactive countermeasures to address or mitigate the underlying contributing factors for the given site. This guide demonstrates the value of using the Haddon Matrix as part of a comprehensive approach to identify underlying crash contributing factors and targeted countermeasures. Chapter 6 (page 6.2) of the Highway Safety Manual provides further discussion of the Haddon Matrix.(1) Refer to the Reliability of Safety Management Methods: Diagnosis for further details related to the use of the Haddon Matrix in identifying crash contributing factors.

After identifying potential countermeasures to target the underlying issues, there is a need to estimate the safety impact of countermeasures, individually and in combination. Analysts consider positive and negative safety impacts, including contraindications under the specific site conditions (e.g., noise from transverse rumble strips near residences). Note countermeasures may produce different results when implemented at different sites with different geometric and operational characteristics. Subsequent steps of the roadway safety management process (economic appraisal and project prioritization) include the consideration of parameters such as constructability, environmental impacts, and cost. The following is a summary of three methods, listed in order of increasing reliability, for comparing countermeasures: judgment-based, data-driven behavioral-based, and data-driven crash-based.

> Contraindications are negative outcomes measured or observed for specific site conditions after implementation of a given measure.

- **Judgment-based**: Professional judgment is critical for all aspects of safety management, including the selection of countermeasures. Based on experience, a person can select appropriate countermeasures to address or mitigate a given issue. While judgment is important, a purely judgment-based method is the least reliable for assessing countermeasures because it is limited by personal experience and susceptible to personal bias and experience that may be relatively limited. Note the significant benefit of using a multidisciplinary team to diagnose issues and select countermeasures. Such a team brings the combined experience, limits the influence of personal bias, and leads to a multidisciplinary-based selection of countermeasures.

- **Data-driven behavior-based**: A data-driven behavior-based method is more reliable than judgment-based only when assessing countermeasures. This method draws on results from research studies of previous applications. While the results do not provide a direct estimate of the expected change in crashes, the performance measures help to determine the expected effect on road user behavior. Data-driven behavioral-based performance measures may include speed, conflicts, lane keeping, and compliance with traffic control devices.
- **Data-driven crash-based**: A data-driven crash-based method is the most reliable for assessing countermeasures. This method draws on the results from research studies of previous applications and provides a direct estimate of safety performance. Analysts use CMFs to quantify and compare the safety effects of potential countermeasures for the specific site conditions. While data-driven crash-based methods are the most reliable for assessing countermeasures, there are a number of considerations to improve the reliability of results. The following are four specific considerations related to the application of CMFs in countermeasure assessment.
    - **Expected versus Observed Crashes:** To apply CMFs, there is a need to estimate future crashes without treatment (i.e., the do-nothing alternative). This guide demonstrates the value of using the Empirical Bayes (EB) method to develop a more reliable estimate of future crashes without treatment compared to historical observed crashes alone (i.e., recorded crash counts). Specifically, the EB method combines historical observed crashes with predicted crashes from a safety performance function (SPF) to overcome issues related to the variability in crashes and changes in traffic volume over time.
    - **Standard Errors of CMFs:** CMFs provide a point estimate of the safety effects of a countermeasure. This guide demonstrates the value of incorporating the standard error of the CMF to understand the potential range of safety effects rather than using the point estimate alone.
    - **Applicability of CMFs:** It is important to assess potential countermeasures in the context of the given site characteristics to determine their applicability and anticipated safety effectiveness. Given multiple CMFs for a countermeasure, it is more appropriate to use an applicable CMF compared to a less applicable, or generic CMF. A generic CMF is a CMF derived from an evaluation of the application of a given countermeasure at a mixture of sites such as urban, suburban, and rural all-way stop controlled intersections. This guide demonstrates the value of using more applicable CMFs to estimate the safety benefit of a potential countermeasure compared to generic CMFs.
    - **Reliability of CMFs:** Given multiple CMFs for a specific countermeasure, it is more appropriate to use a higher quality CMF compared to a lower quality CMF. CMF quality is determined by the relevant evaluation's study design, data attributes, evaluation method and potential biases, sample size, and standard error. Note the standard error indicates the accuracy and precision of the resulting CMF. This guide demonstrates the value of using higher quality CMFs to estimate the safety benefit of a potential countermeasure compared to lower quality.

The following section describes the use of the Haddon Matrix and data-driven methods in countermeasure selection. It begins with a discussion and example of the Haddon Matrix because this is the first step in selecting countermeasures. Next, the section provides a discussion of data-driven crash-based methods to apply CMFs in countermeasure selection. Examples illustrate the potential difference in results by using more reliable methods to apply CMFs in a data-driven crash-based method. The section concludes with a discussion and example of the data-driven behavior-based method, which is necessary when CMFs are not available for the countermeasure(s) of interest. The use of more reliable, data-driven countermeasure selection methods will generally lead to the selection of targeted, effective, and defensible countermeasures to mitigate specific safety issues.

3. DEMONSTRATING THE VALUE OF MORE RELIABLE METHODS

This section demonstrates the value of applying more reliable methods in countermeasure selection to identify targeted countermeasures, quantify the effectiveness of potential countermeasures, and consider the range in the effectiveness of potential countermeasures. Empirical examples highlight the shortcomings of less reliable methods, which may lead to less reliable results and conclusions. Note the examples illustrate the general comparative results of the methods. Different scenarios and different data will produce different results. In general, the examples demonstrate the value of applying more reliable countermeasure selection methods.

THE HADDON MATRIX

The Haddon Matrix is a comprehensive tool to identify suitable and effective countermeasures to mitigate a substantiated safety issue. During step 2 of the safety management process (diagnosis), the multidisciplinary analysis team (namely, the Team) reviews past crash data in conjunction with attributes of the road users, adjacent land use, geometry, and traffic operations of the study location. This includes the identification of target crash types and crash contributing factors, which provides the foundation for the identification and selection of appropriate countermeasures.

Using the Haddon Matrix will help you select more effective countermeasures suitable to the site of interest.

The Haddon Matrix supports a comprehensive approach to understanding crash contributing factors as shown in Table 1. The Team would complete the Haddon Matrix for each target crash type identified during diagnosis. Following the completion of the Haddon Matrix, the Team can identify potential countermeasures to directly target underlying contributing factors. Less effective countermeasures may result if the Team does not consider the site-specific and multiple factors contributing to past or potential crashes.

The Haddon Matrix is comprised of nine cells to identify human, vehicle, and roadway factors contributing to the target crash type or severity outcome before, during, and after the crash. Examples of human factors include distraction, fatigue, and seat belt use. Examples of vehicle factors include worn brakes, headrest design, and airbag operation. Examples of roadway factors include wet pavement, snow-limiting visibility, signal coordination, and steep grade.

Table 1. Haddon Matrix.

Period	Human Factors	Vehicle Factors	Roadway Factors
Before (causes of hazardous situation)			
During (causes of crash severity)			
After (factors of crash outcome)			

The contributing factors originate from careful review of police crash reports and summary data (e.g., collision diagrams), review of design drawings and traffic operations, and observations during field investigations. The following is an example application of the Haddon Matrix.

Example 1: Application of the Haddon Matrix

An agency performed network screening to identify sites that warrant further investigation based on their potential for safety improvement. One site is a four-leg signalized intersection in an urban area (see Figure 3). During diagnosis, a multidisciplinary team identified right-angle and left-turn crashes as target crash types for further consideration. Note one team member suggested a red-light-running camera to mitigate right-angle crashes prior to a comprehensive investigation.

The Team then conducted a comprehensive investigation, including the completion of the Haddon Matrix based on the data and information collected for right-angle and left-turn crashes. Table 2 presents their results.

After careful study of the Haddon Matrix, the Team summarized their conclusions. First, novice drivers accessing the high school located in the southwest quadrant of the intersection have inadequate sight distance to southbound vehicles due to the vertical and horizontal alignments. Further, left turn movements require experience in checking for pedestrians as well as judging gaps (i.e., assessing the approach distance and speed of oncoming vehicles). The combination of limited sight distance to and from the intersection, and high approach speeds on the southbound approach, contributed to many of the severe right-angle and left-turn crashes. A similar safety issue occurs when senior drivers attend community events at the school in the evening. Figure 3 presents a diagram of the study intersection with identified issues.

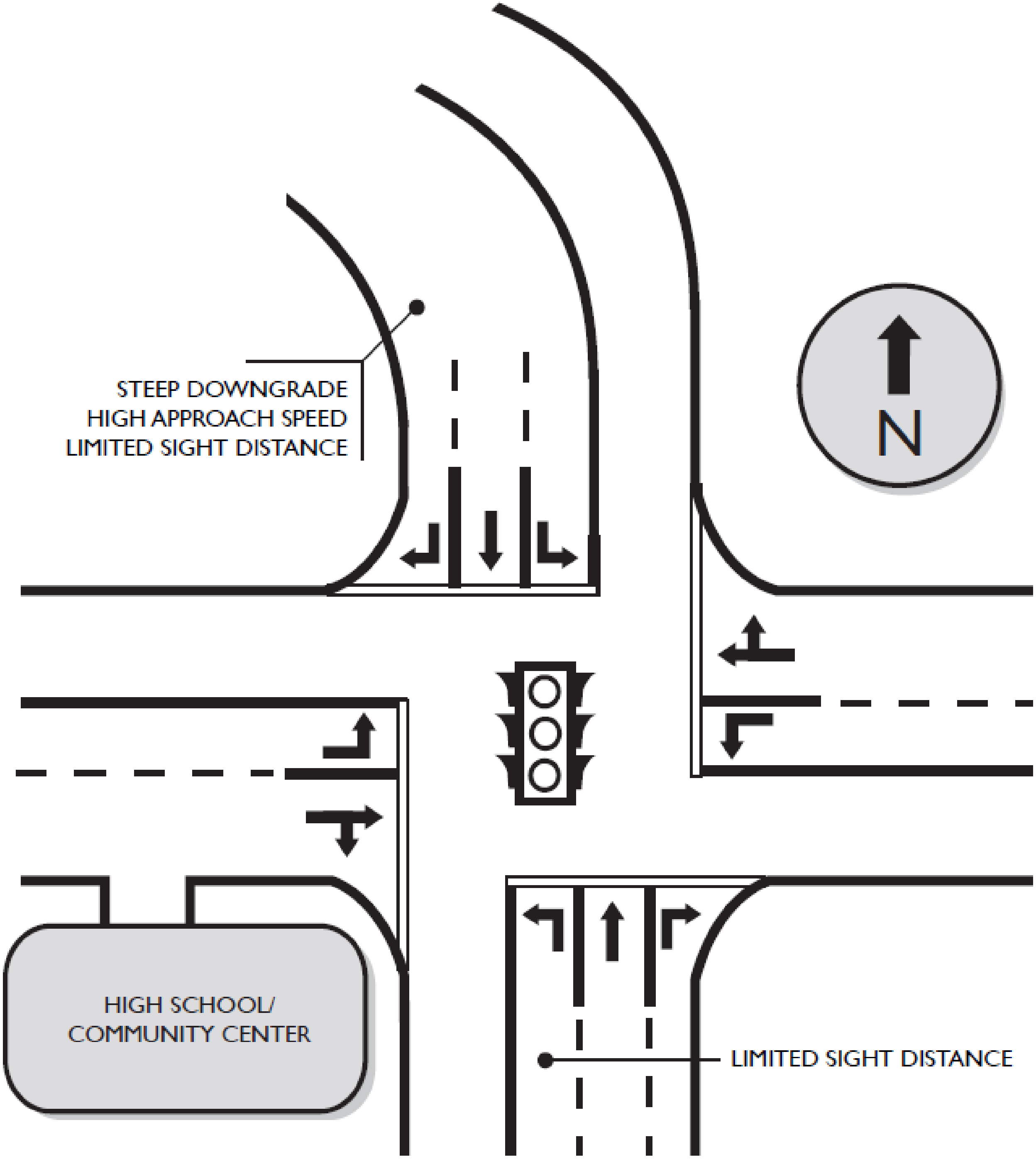


Figure 3. Diagram. Diagram of study intersection for example 1.

Table 2. Example 1 Haddon Matrix for right-angle and left-turn crashes.

Period	Human Factors	Vehicle Factors	Roadway Factors
Before (causes of hazardous situation)	• Drivers running red light - inadequate sight distance and issues processing information (gap judgment) • Drivers turning left (northbound-west) - inadequate sight distance and issues processing information (gap judgment) • High speed corridor leading to high intersection approach speeds (downgrade on southbound approach) • High school and community center near intersection - novice drivers (daytime hours) and senior drivers (evening hours)	• Bald tires	• Combination of horizontal and vertical alignment (southbound approach) • Limited sight distance for left-turn drivers • Limited sight distance to intersection (southbound approach) • Permissive left-turn phase only
During (causes of crash severity)	• Vulnerability to injury	• Side impact • No airbags	• Utility pole on the sidewalk
After (factors of crash outcome)	• Age	• No factors identified	• Emergency response time

Based on the identified target crash types and crash contributing factors, the Team selected the following infrastructure-related countermeasures for further consideration.

- **Signal phase modification (short-term)**: Modify the permissive left-turn phase to a protected left-turn phase and install a nearside supplemental traffic signal head for southbound drivers approaching the intersection. Note there is a dedicated left-turn lane on all approaches.
- **Advance warning flashers (short-term)**: Install an advance warning sign (‘signal ahead’ or ‘be prepared to stop’) with continuous flashers on the southbound approach.
- **Roundabout (long-term)**: Convert the signalized intersection to a two-lane modern roundabout with additional alignment improvements to the north leg of the intersection.

In comparison, the Team determined a red-light-running camera system is not suitable for this intersection. Following the comprehensive review, the Team identified limited sight distance and high approach speeds as factors contributing to right-angle crashes, not driver disobedience. Therefore, red-light cameras would not have treated the target crash type as demonstrated by the comprehensive and holistic method using the Haddon Matrix. In conclusion, preventing the installation of red-light cameras at this location demonstrates the value of using this more comprehensive and reliable analysis via the Haddon Matrix.

The agency would pay $30,000 to modify the signal phases and $500 for the advance warning flashers. Both of these improvements are expected to mitigate the contributing factors to the right-angle and left-turn target crashes. In comparison, the agency would pay $75,000 for a red-light camera installation, which is not likely to mitigate the target crashes in this particular scenario. This example demonstrates the value of using more reliable methods to identify targeted countermeasures.

DATA-DRIVEN CRASH-BASED METHOD

The data-driven crash-based method is the most reliable countermeasure selection method because it provides a direct indication of safety performance and minimizes the influence of personal bias. This method relies on CMFs to quantify and compare the safety effects of potential countermeasures. While CMFs provide a direct comparison of safety performance, the following are four considerations related to the application of CMFs. As detailed in the remainder of this section, proper consideration of these factors helps to improve the reliability of results.

- Expected versus observed crashes.
- Standard Errors of CMFs.
- Applicability of CMFs.
- Reliability of CMFs.

Expected versus Observed Crashes

This section demonstrates the value of using expected crashes as compared to observed crash history to estimate future crashes without the implementation of a potential countermeasure (i.e., the do-nothing alternative at a future time). This provides a more reliable baseline for applying an appropriate, high-quality CMF to estimate the safety effectiveness of a contemplated countermeasure. More reliable estimations of the benefits or disbenefits in terms of change to future expected crashes (by type and severity) for potential countermeasures will provide more defensible selection of countermeasures. Note these benefit or disbenefit estimations are also fundamental to a more reliable economic appraisal (step 4 of the road safety management process) and subsequent project prioritization (step 5 of the road safety management process). A less rigorous alternative to using the expected crashes is to estimate future crashes without treatment based on the short-term observed crash history. An example is provided later in this section.

You can achieve a more stable measure and overcome the volatility of short-term crash counts by estimating the long-term safety performance of the location of interest. The long-term safety performance is expressed as the expected average crash frequency.

During the past decades, safety professionals studied historical crash records with the intent of learning about crash trends. In doing so, they realized the volatility of annual reported crashes (i.e., observed crash frequency) and short-term averages did not represent the long-term safety performance of a facility.(3) Figure 4 illustrates this volatility where the short-term average is much different from the long-term expected average safety performance. Further, researchers determined it is necessary to consider the changes in annual traffic volume when estimating the long-term safety performance of a facility. It became evident there was a potential to combine this information (i.e., observed crashes and traffic volume) to improve the estimate of the long-term safety performance. As a result, researchers adapted the EB method to meet the need for a reliable safety analysis.

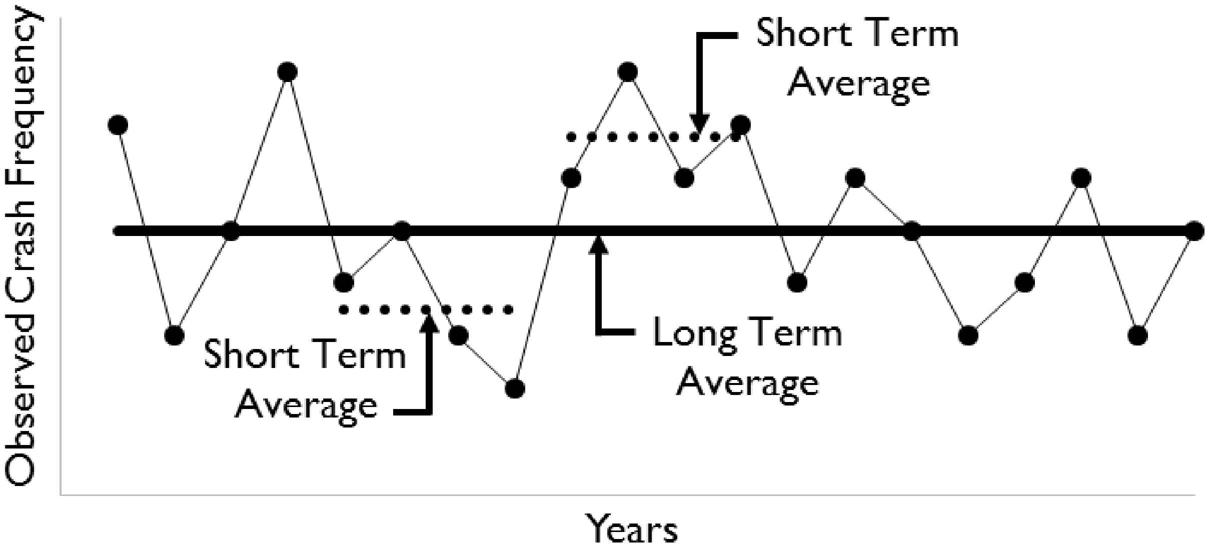


Figure 4. Chart. Short-term (observed) and long-term (expected) average crash frequency.

The Highway Safety Manual and Hauer present the details of the EB method.(1,3) In general, the EB method combines the short-term observed crash history with the predicted crashes at the site of interest. An equation, namely a safety performance function (SPF), is used to compute the predicted crash frequency (by crash severity and by crash type) for a given traffic volume. The SPF is a best-fit model relating annual observed crashes to the annual traffic volume for a group of sites with similar attributes as shown in Figure 5. In Figure 5, the points represent observed crashes at specific traffic volumes for individual sites, and the solid line represents the best-fit model (i.e., the SPF). The homogeneity of the individual sites and their combined historical data help to overcome the limitations of short-term crashes for any one site. Similar sites are typically grouped by the respective facility type such as rural two-lane roads, urban four-legged signalized intersections, and rural multilane divided highways. For example, an agency may group 300 rural, two-lane road segments to create one site subtype, and separately group 60 urban, four-legged, signalized intersections to create another site subtype.

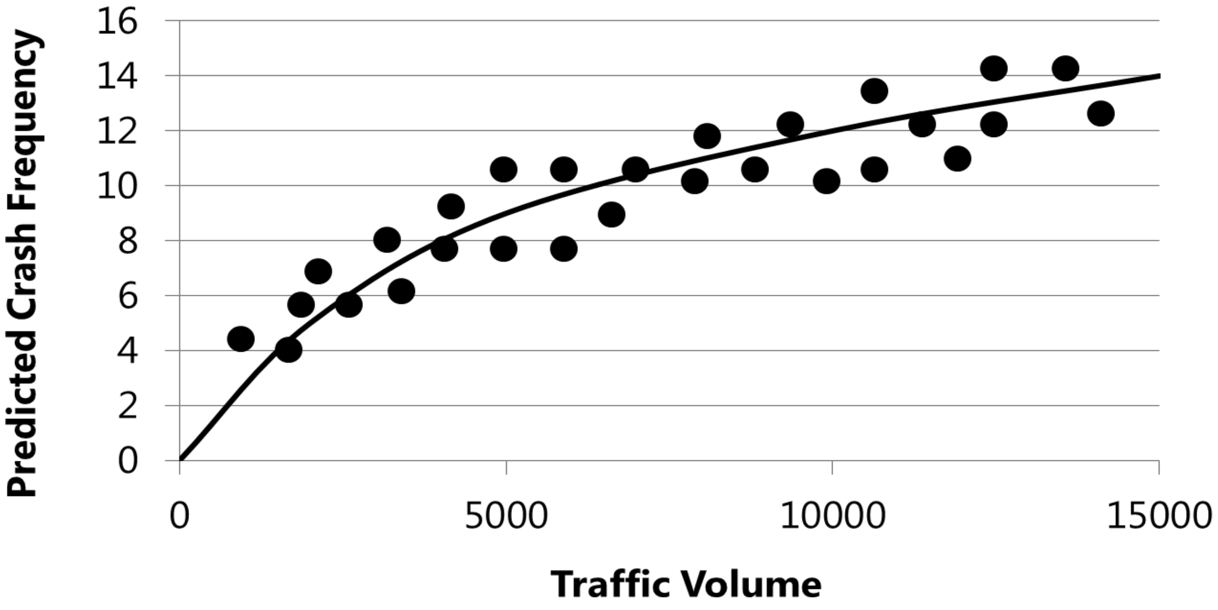


Figure 5. Graph. Example SPF relating crash frequency and traffic volume.

The expected crash frequency estimated with the EB method provides a better estimate of the long-term average safety performance than the observed crash history alone.(3) Further, analysts can calculate the expected crash frequency with a high level of accuracy even with one or two years of recorded crashes for the site(s) of interest. The EB method also allows for the estimation of crashes in future years using forecasted traffic volumes, and assuming no other changes to the site(s). Analysts can apply CMFs to these more reliable estimates of expected crash frequency to facilitate more reliable decision-making. In summary, location-specific traffic and crash data, and a relevant SPF, facilitate the use of more reliable methods (e.g., the EB method) to estimate crash frequency and severity. Hauer provides evidence of the applicability and reliability of the EB method with supporting data-driven examples.(3)

The following example demonstrates the value of using SPFs and the EB method to estimate the safety impacts of a potential countermeasure. The example also demonstrates the potential shortcomings of using short-term crash counts for individual locations, which is also an issue when analyzing multiple locations.

Example 2: Application of SPFs and the EB Method to Estimate Expected Crashes

This example illustrates the use of SPFs and the EB method for a rural two-lane roadway segment of 1.152 mi and an annual average daily traffic (AADT) volume of 4,825 vehicles per day. Over the five-year study period, there were 15 fatal and injury (F+I) and 55 property damage only (PDO) crashes recorded. An agency developed the SPFs and over-dispersion parameters (k) shown in Figure 6 and Figure 7 for rural, two-lane roadway segments.

$$N_{SPF}\ (F+I) = 8.08 * 10^{-3} * L * AADT^{0.4821};\ k = 0.35$$

Figure 6. Equation. SPF for fatal and injury crashes.

$$N_{SPF}\ (PDO) = 2.005 * 10^{-2} * L * AADT^{0.4821};\ k = 0.35$$

Figure 7. Equation. SPF for PDO crashes.

where:

N_{SPF} (F+I) = predicted number of fatal and injury crashes.
N_{SPF} (PDO) = predicted number of PDO crashes.
L = segment length (mi).
AADT = traffic volume (vehicles per day).
k = over-dispersion parameter.

Figure 8 and Figure 9 show the calculations of predicted crash frequencies for the study period, substituting the segment length (1.152 mi) and traffic volume (4825 vehicles per day).

$$N_{SPF}\ (F+I) = 8.08 * 10^{-3} * 1.152 * 4825^{0.4821} = 0.555 \text{ F+I crashes/year}$$

Figure 8. Equation. Example calculation using SPF for fatal and injury crashes.

$$N_{SPF}\ (PDO) = 2.005 * 10^{-2} * 1.152 * 4825^{0.4821} = 1.378 \text{ PDO crashes/year}$$

Figure 9. Equation. Example calculation using SPF for PDO crashes.

Figure 10 shows the equation to compute the weight adjustment for use in the EB method.

$$w = 1 / [1 + k * (\Sigma \text{ all years } N_{spf})]$$

Figure 10. Equation. Weight adjustment for EB method.

where:

w = weight adjustment for the predicted crashes.

All other terms as previously defined.

Figure 11 and Figure 12 show the weight adjustment factor calculations for F+I and PDO crashes. Note the study period is five years and the traffic volume represents the average over the five-year period (i.e., predicted crashes are the same for each of the five years).

$$w\ (F+I) = 1 / [1 + 0.35 * (5 * 0.555)] = 0.507$$

Figure 11. Equation. Weight adjustment for fatal and injury crashes.

$$w\ (PDO) = 1 / [1 + 0.35 * (5 * 1.378)] = 0.293$$

Figure 12. Equation. Weight adjustment for PDO crashes.

Figure 13 shows the equation for the EB method, which is applied to compute the expected crashes ($N_{expected}$) for the study period.

$$N_{expected} = w * N_{SPF} + (1 - w) * N_{observed}$$

Figure 13. Equation. EB method.

Figure 14 and Figure 15 show the calculations of the expected F+I and PDO crashes. Note the computations include crashes per year. As such, the equations include the predicted crashes (N_{SPF}) per year (0.555 F+I crashes per year and 1.378 PDO crashes per year) and the observed crashes ($N_{observed}$) per year (15/5 = 3.0 F+I crashes per year and 55/5 = 11.0 PDO crashes per year).

$$N_{expected}\ (F{+}I) = 0.507 * 0.555 + (1 - 0.507) * 3.0 = 1.760\ \text{F+I crashes/year}$$

Figure 14. Equation. Example calculation of expected fatal and injury crashes.

$$N_{expected}\ (PDO) = 0.293 * 1.378 + (1 - 0.293) * 11.0 = 8.181\ \text{PDO crashes/year}$$

Figure 15. Example calculation of expected PDO crashes.

To estimate the expected F+I and PDO crashes, the SPF is used with the average traffic volume for the five-year study period (i.e., 4,825 vehicles per day). For this example, the analysts assume the traffic volume will increase in the next few years to an average of 6,500 vehicles per day. Assuming the SPF will remain relevant to the following years of crash and traffic data for this type of rural two-lane roadway, the predicted F+I and PDO crash frequencies will increase proportionally to the increase in traffic volume. Figure 16 and Figure 17 show the computations to adjust the predicted F+I and PDO crash frequencies based on the proportion of future to present traffic volumes.

$$N_{SPF}\ (F{+}I)\ \text{future} = 0.555 * (6{,}500 / 4{,}825)^{0.4821} = 0.555 * 1.154 = 0.640\ \text{F+I crashes/year}$$

Figure 16. Equation. Example calculation of future predicted fatal and injury crashes.

$$N_{SPF}\ (PDO)\ \text{future} = 1.378 * (6{,}500 / 4{,}825)^{0.4821} = 1.378 * 1.154 = 1.590\ \text{PDO crashes/year}$$

Figure 17. Equation. Example calculation of future predicted PDO crashes.

Assuming the same proportional increase, Figure 16 and Figure 17 show the computations to estimate the expected crash frequencies for the future period.

$$N_{expected}\ (F{+}I) = 1.760 * 1.154 = 2.03\ \text{F+I crashes/year}$$

Figure 18. Equation. Example calculation of future expected fatal and injury crashes.

$$N_{expected}\ (PDO) = 8.181 * 1.154 = 9.44\ \text{PDO crashes/year}$$

Figure 19. Equation. Example calculation of future expected PDO crashes.

Table 3 shows the differences between the five-year observed average crash frequencies based on crash counts alone and the expected average crash frequencies from the EB method.

Table 3. Difference between observed and expected crashes.

Crash Type	Observed Crashes (past 5 year period)	Expected Crashes (past 5 year period)	Expected Crashes (future period)
F+I crashes	3.0	1.76	2.03
PDO crashes	11.0	8.18	9.44

This example illustrates the differences that would be carried into estimations of treatment effectiveness and economic analyses. The five-year (short-term) average observed PDO crashes are 34 percent greater than the five-year average expected (long-term) PDO crashes; the average observed F+I crashes are 70 percent greater than the expected. Thus, had the observed values been used in the analysis, the calculations would be based on a considerable overstating of the severity and frequency of crashes. The use of the state-of-the-art EB method, and the resulting expected crashes provides a more reliable (and stable) basis to estimate changes in safety performance. The remainder of this example demonstrates how these differences propagate through the economic appraisal step and contribute to potential misleading estimations.

During the comprehensive diagnosis step, the crash summaries show 64 percent of all crashes recorded along this rural, two-lane road segment were single-vehicle run-off-road (SVROR) crashes, with a high proportion of F+I crashes. This proportion is quite higher than the default value of 52.1 percent shown in the Highway Safety Manual (Table 10-4), which is based on data from the State of Washington.(1) Thus, the Team identified SVROR as the target crash type for consideration in countermeasure selection. Further, the Team noted some crash-involved drivers might have been fatigued due to the long commuting trips along this corridor. After confirming there were no residential or commercial buildings within 1,000 feet, the Team suggested shoulder rumble strips, among other countermeasures, to address SVROR crashes.

While searching the Highway Safety Manual and CMF Clearinghouse for relevant CMFs, the Team identified a study by Torbic et al. in the CMF Clearinghouse.(4) The Team downloaded the full report via the CMF Clearinghouse and, after reviewing the extensive research study, decided to use the CMFs recommended by the researchers for inclusion in the Highway Safety Manual. The shoulder rumble strip CMF for all SVROR crashes (all severities) is 0.84 with a standard error of 0.08. [Note the following section provides a detailed discussion of the standard error of a CMF and an example application.] The shoulder rumble strip CMF for F+I-related SVROR crashes is 0.64 with a standard error of 0.10. Note these CMFs reflect data from similar rural two-lane roadways, with traffic volumes from approximately 900 to 9,000 vehicles/day.

To illustrate the calculations, future expected SVROR crashes without treatment are estimated from the total future expected crashes without treatment (i.e., the sum of future expected F+I and future expected PDO crashes), and assuming a similar proportion of SVROR collisions as the observed crash history (i.e., 64 percent of all crashes). The Team then applied the applicable CMFs to the future expected SVROR crashes *without* treatment to estimate the future expected SVROR crashes *with* treatment. Figure 20 through Figure 22 show the computations to demonstrate this process.

Future Expected Total Crashes <u>without</u> Treatment = 2.03 F+I + 9.44 PDO = 11.47 crashes/year

Figure 20. Equation. Example calculation of future expected total crashes without treatment.

Future Expected SVROR Crashes <u>without</u> Treatment = 0.64 * 11.47 = 7.51 crashes/year

Figure 21. Equation. Example calculation of future expected SVROR crashes without treatment.

Expected Change in SVROR Crashes <u>with</u> Treatment = 7.51 * (1 - 0.84) = 1.20 crashes/year

Figure 22. Equation. Example calculation of change in expected SVROR crashes with treatment.

Using the expected crashes from the EB method, the result is an estimated savings of 1.20 SVROR crashes per year (on average). The estimated safety effects would be different if the Team used the average observed crash history to estimate future crashes without treatment. Specifically, Figure 23 through Figure 25 show the estimated savings is 1.43 SVROR crashes per year (on average) when using the observed crash history. This leads to a relatively larger value of safety benefits compared to the use of expected crashes. Specifically, the difference is 1.43 – 1.20 = 0.23 SVROR crashes/year, as shown below:

Observed Total Crashes <u>without</u> Treatment = 3.0 F+I + 11.0 PDO = 14.0 crashes/year

Figure 23. Equation. Example calculation of future total crashes without treatment based on observed crashes.

Calculated SVROR Crashes <u>without</u> Treatment = 0.64 * 14.0 = 8.96 crashes/year

Figure 24. Equation. Example calculation of future SVROR crashes without treatment based on observed crashes.

Calculated Change in SVROR Crashes <u>with</u> Treatment = 8.96 * (1 - 0.84) = 1.43 crashes/year

Figure 25. Equation. Example calculation of change in SVROR crashes with treatment based on observed crashes.

The results from step 3 (countermeasure selection) of the roadway safety management process are brought forward to the next step (economic appraisal) to determine the benefit-cost of such a project. It is important to use accurate estimates of the benefit for the economic analysis; otherwise, the Team may incorrectly estimate the benefit-cost ratio, and incorrectly support or refute the implementation of a contemplated countermeasure.

In summary, the use of SPFs and the state-of-the-art EB method to estimate expected crashes helps to account for the random variation in crashes (i.e., volatility) and changes in traffic volume over time. Using the observed crash history, the estimate of SVROR crashes without treatment (8.96 crashes/year) is 1.45 crashes/year (19 percent) higher than the expected SVROR estimate of 7.51 crashes/year. This is overstating of the annual SVROR estimate represents the short-term average crash count without accounting for the regression-to-the-mean, as noted in Hauer.(3) On a network level, such differences are even more important.

In conclusion, the use of expected crashes provides a more reliable estimate of future crashes without treatment compared to the use of observed crashes. Further, the use of expected crashes provides more reliable estimates of the safety benefit, and leads to more defensible decision-making regarding whether to implement a countermeasure or not. It is noted the Team can achieve even more reliable estimates of expected crashes by applying the EB method for each individual year and then aggregating the results (as opposed to using average traffic volume and observed crashes over a multiyear study period) as shown in the Highway Safety Manual Part A, Chapter 3, and Part C, Appendix A.(1)

You can overcome the issue of short-term variability of crash counts to develop a more reliable estimate of countermeasure effectiveness by using the EB method to estimate the expected crash frequency and severity for an intersection or a road section.

Standard Errors of CMFs

This section demonstrates the value of using a CMF and the associated standard error to estimate the range of possible safety benefits versus using the point estimate of the CMF to estimate a single value.

The Highway Safety Manual provides the standard error of the CMF along with the point estimate of the CMF.(1) It reads (page 3-22):

"The standard error of an estimated value serves as a measure of the reliability of that estimate. The smaller the standard error, the more reliable (less error) the estimate becomes…Standard error can also be used to calculate a confidence interval for the estimated change in expected average crash frequency."

Figure 26 shows the equation used to compute the confidence interval.

$$\text{Confidence Interval} = \text{CMF} \pm (\text{Multiplier} * \text{Standard Error})$$

Figure 26. Equation. Confidence interval.

Analysts establish the desired level of confidence (e.g., 90 or 95 percent) by selecting the probability that the true value of the safety impact of a given countermeasure is within the confidence interval. Table 3-3 of the Highway Safety Manual indicates the following values for determining confidence intervals using the standard error.(1)

- Use a multiplier of 1.0 for a 65 to 70 percent confidence level.
- Use a multiplier of 2.0 for a 95 percent confidence level.
- Use a multiplier of 3.0 for a 99 percent confidence level.

Note these multipliers differ slightly from standard statistical texts and provide approximations of the confidence interval. The following example demonstrates the value of using the 95 percent confidence interval, as chosen by the Team, to estimate the range of potential benefits when selecting countermeasures.

Example 3: Application of the Standard Error of a CMF to Estimate Variability

Continuing the example illustrated in Example 2 above, the CMF for installing shoulder rumble strips is 0.84 with a standard error of 0.08. This CMF applies to all single-vehicle run-off-road (SVROR) crashes (all severities). Figure 27 shows the computation of the 95 percent confidence interval.

$$95\%\ \text{Confidence Interval} = \text{CMF} \pm (2.0 * \text{Standard Error}) = 0.84 \pm (2.0 * 0.08) = [0.68,\ 1.0]$$

Figure 27. Equation. Example calculation of confidence interval.

This confidence interval implies, with 95 percent certainty, the true value of the safety effect of installing shoulder rumble strips is within the values of 0.68 to 1.0. This range of values indicates shoulder rumble strips may reduce future SVROR crashes by up to 32 percent or have no impact at all (i.e., CMF of 1.0 implies no change in future crash frequency).

The Team carried the range of estimates for a selected confidence interval forward to step 4 of the safety management process (economic appraisal). Continuing with Example 2, and using the EB method, they considered the scenario with 7.51 expected crashes per year without treatment. Figure 28 and Figure 29 show the computation of the range of potential effects for installing shoulder rumble strips based on the 95 percent confidence interval.

$$\text{Lower bound of expected change in SVROR crashes} = 7.51 * (1 - 1.0) = 0\ \text{crashes/year}$$

Figure 28. Equation. Example calculation of lower bound of expected change in SVROR crashes.

$$\text{Upper bound of expected change in SVROR crashes} = 7.51 * (1 - 0.68) = 2.4\ \text{crashes/year}$$

Figure 29. Equation. Example calculation of upper bound of expected change in SVROR crashes.

Assuming an average cost of $100,000 per SVROR crash, the annual benefit of installing shoulder rumble strips along this corridor of Example 2 may range from $0 to $240,000. [Note in the absence of agency-specific crash costs, analysts may refer to FHWA's Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries.](5)

To estimate the benefit-cost ratio, convert the annual benefit to a present value and compare to the present value of construction and annual maintenance costs. Using the range of annual benefits, the Team computed the associated range in benefit-cost ratio. Refer to the Highway Safety Manual or FHWA's *CMFs in Practice: Quantifying Safety in the Roadway Safety Management Process* for further discussion of computing benefit-cost ratios.(1,6)

The standard error of a CMF provides decision-makers with a broader understanding of the potential effects of contemplated countermeasures. Specifically, the standard error is necessary to estimate the potential range of safety effects and associated crash costs for a given countermeasure. Using this information, agencies can calculate the range of economic returns (positive and negative). Alternatively, using only the point estimate (average value) of the CMF results in a single value of the potential safety effect, hence, ignoring the potential range of effects, which may even indicate a potential increase in crashes, for the countermeasure under certain site conditions.

> The standard error of a CMF for a given countermeasure determines the interval of possible estimates of the safety effect (with the selected level of confidence) after implementation of the given countermeasure.

Applicability of CMFs

This section demonstrates the value of using an applicable CMF as compared to a less applicable CMF to estimate the safety benefit of a potential countermeasure. The anticipated safety effect of a contemplated countermeasure is one factor that influences the decision to implement or not implement the countermeasure at a specific site. Note when the safety effectiveness of a particular countermeasure can be quantified along with other non-safety parameters, such as operational performance, environmental impacts, and cost, these factors are jointly considered in the decision-making process.

Several countermeasures that mitigate contributing factors of a given crash type may be suitable and may be considered for different roadway environments and site attributes. Such an example is the installation of shoulder rumble strips along rural two-lane highways, multilane highways, or freeways. Another example is the conversion of a rural all-way stop-controlled intersection or an urban four-leg signalized intersection to a modern roundabout. The safety effect of such countermeasures, however, may not be equal in different settings (e.g., the safety effect of converting an intersection to a roundabout will likely differ for urban and rural applications as well as applications to stop-controlled and signalized intersections).

CMFs are the result of safety studies that evaluate the effects of a given countermeasure (or combination of measures) under specific site conditions. These site conditions determine the applicability of the resulting CMF for use at other similar locations when considering the implementation of the given countermeasure. For example, assume a safety evaluation study to develop a CMF for shoulder rumble strips includes sites with the following characteristics:

- Facility type: two-lane rural highways.
- Traffic volumes: up to 20,000 vehicles per day.
- Shoulder widths: four to six feet.

The resulting CMF is applicable when considering the installation of shoulder rumble strips for similar site conditions. Users should not assume such a CMF is applicable to the installation of shoulder rumble strips on four-lane freeways with traffic volumes up to 45,000 vehicle/day, and shoulder widths of eight feet. Thus, it is important for the analysts to identify the applicability of the CMF to their specific project/s.

Part D of the Highway Safety Manual presents CMFs along with attributes to determine applicability.(1) These attributes include the base condition prior to the treatment, the setting (e.g., urban or rural, signal or stop-controlled, etc.), the traffic volume range, and the target crash type and severity. At times, the Highway Safety Manual does not provide details about one or more of these attributes due to missing information in the original study documentation. The CMF Clearinghouse also provides these and other details to help users determine the applicability of CMFs.

The following example demonstrates the value of considering the specific site attributes and applicability when selecting and applying a CMF for a potential countermeasure.

Example 4: Application of Applicable CMFs to Improve Reliability of Estimates

An agency has selected an intersection as a site with high potential for improvement during network screening. The following are specific site attributes.

- Area type: urban.
- Geometry: four-leg intersection.
- Traffic control: all-way stop-controlled.
- Total entering traffic volume: 5,500 vehicles per day.

Subsequently, a multidisciplinary team performed a comprehensive diagnostic investigation, using the five-year crash history to identify target crash types, and using the Haddon Matrix to identify factors contributing to these crashes. The Team recommended the conversion of the stop-controlled intersection to a single-lane roundabout as a potential countermeasure.

The Team proceeded to search for suitable CMFs. Part D of the Highway Safety Manual (Table 14-4) does not include a CMF specifically for such intersection attributes.(1) Instead, there is a CMF of 1.03 with a standard error of 0.2 (relevant to all crash types and severities combined) which is applicable to converting all-way stop-controlled intersections to roundabouts for all settings combined (i.e., urban or rural, one- or two-lane intersections, unspecified traffic volumes, and all crash types and severities).(7) This is an example of a non-specific (generic) CMF.

The CMF Clearinghouse provides other CMFs for the same conversion and includes additional site attributes. It also provides separate CMFs for specific site characteristics. Table 4 presents the CMFs and associated standard errors for the conversion of all-way stop-controlled intersections to a single-lane roundabout. Table 4 indicates the CMFs vary by the site conditions and target crash. In general, the results indicate greater reductions in urban areas and for fatal and injury crashes.

For total crashes (all types and severities), the CMFs indicate a 72 percent reduction for urban conversions and a 58 percent reduction for rural conversions. For fatal and injury crashes, the CMFs indicate an 88 percent reduction for urban conversions, and an 82 percent reduction for rural conversions.

Table 4. CMFs for converting all-way stop-controlled intersection to single-lane roundabout.(8)

Crash Type	Crash Severity	Area Type	CMF	Standard Error
All	All	Urban	0.28	0.11
All	All	Rural	0.42	0.13
All	Fatal and Injury	Urban	0.12	0.14
All	Fatal and Injury	Rural	0.18	0.16

Based on the specific site characteristics and the results from Table 4, the most applicable CMF for total crashes is 0.28±0.11 (at two standard errors, the effect is estimated to be within the range of 50 to 94 percent reduction in total crashes) and the most applicable CMF for fatal and injury crashes is 0.12±0.14 (at two standard errors, the effect is estimated to be within the range of 60 to 100 percent reduction in fatal and injury crashes). Thus, the Team concluded the conversion of the all-way stop-controlled intersection to a single-lane roundabout would likely, at a 95 percent confidence level, lead to a large reduction in future total crashes and fatal and injury crashes. In comparison, the non-specific (generic) CMF of 1.03±0.2 from the Highway Safety Manual indicates at two standard errors, the effect ranges from a 37 percent reduction to a 43 percent increase in future total crashes.

In conclusion, the CMF for the specific site attributes (i.e., conversion of an urban, all-way stop-controlled intersection to a single-lane roundabout) is quite distinct to a different setting (e.g., rural or combined settings). The use of non-specific (generic) CMFs could lead to deferring the option of a roundabout at this site, or lead to less accurate estimations of the safety effectiveness. These estimations will also affect the subsequent economic appraisal and, project prioritization steps, and the eventual project decision-making. The significant positive impact in reduction of total crashes, and most significantly in fatal and injury crashes, in the example application demonstrates the value of using the applicable CMFs.

When you are searching for the estimate of the safety effect (CMF) of implementing a potential countermeasure, the reliability of your estimates and decision making will increase when using applicable CMFs developed for the specific characteristics of your site of interest.

Reliability of CMFs

This section demonstrates the value of using a higher quality CMF as compared to a lower quality CMF to estimate the safety effect of a potential countermeasure.

Two popular sources of CMFs are the Highway Safety Manual and the web-based CMF Clearinghouse.(1) The following is a brief summary of the Highway Safety Manual and CMF Clearinghouse review and inclusion process.

- **Highway Safety Manual Publication Review Process:** Part D of the Highway Safety Manual includes only the best available research-based CMFs. Prior to accepting or rejecting a CMF for potential inclusion in Part D, reviewers considered study characteristics such as the underlying data, the method used to evaluate the safety effect, and the accuracy and precision of the CMF based on its standard error. The Highway Safety Manual review process applies an adjustment factor to the study's originally published CMF to correct for regression-to-the-mean and traffic volume bias, as needed. The review process also applies a method correction factor to the standard error of the study's CMF to correct for undesirable study characteristics related to the study design, sample size, and confounding factors identified during the critical review of each study. For a detailed description of this procedure and the Highway Safety Manual inclusion process, refer to the Transportation Research Circular E-C124, *Methodology for the Development and Inclusion of Crash Modification Factors in the First Edition of the Highway Safety Manual.*(9)
- **CMF Clearinghouse Publication Review Process:** The CMF Clearinghouse includes all crash-based CMFs related to engineering countermeasures; there is no inclusion criteria. Instead, the CMF Clearinghouse includes a star-quality rating to indicate the quality of each CMF, when possible. At times, study reviewers were not able to assess the quality of some CMFs due to the lack of details about the evaluation study. In these cases, the CMF Clearinghouse marks the quality as "cannot be rated." The website describes the star rating based on a set of criteria: *"The star quality rating indicates the quality or confidence in the results of the study producing the CMF. While the reviewers applied an objective as possible set of criteria, the star quality rating still results from an exercise in judgment and a degree of subjectivity. The star rating is based on a scale (1 to 5), where a 5 indicates the highest or most reliable rating. The review process to determine the star rating judges the accuracy and precision as well as the general applicability of the study results. Reviewers considered five categories for each study — study design, sample size, standard error, potential bias, and data source — and judged each CMF according to its performance in each category."* For a detailed description of this process, refer to the CMF Clearinghouse.

In conclusion, the analyst should seek applicable higher quality CMFs developed from sites similar to the site of interest. An analysis using higher quality CMFs will obtain more reliable estimates as shown in the example below.

Example 5: Application of High Quality CMFs to Improve Reliability of Estimates

Continuing with Example 1 for the four-leg signalized intersection, the Team considered the conversion of the signalized intersection to a two-lane modern roundabout. The Team identified multiple potential CMFs to estimate the safety effects of the conversion.

The Highway Safety Manual provides a CMF for converting an urban four-leg signalized intersection to a modern roundabout where the number of lanes and traffic volume are unspecified (Table 14-3).(1) For total crashes (all crash types and all severities), the CMF is 0.99 with a standard error of 0.1. For fatal and injury crashes (all crash types with injury severity), the CMF is 0.40 with a standard error of 0.1.(7)

The CMF Clearinghouse provides more recent CMFs estimated from similar installations to the site of interest (e.g., urban and suburban, two-lane roundabouts, traffic volumes between 5,300 and 52,000 vehicles/day). The CMFs scored a 4-star quality rating score (QRS) [Score details: study design score: excellent; sample size score: excellent; standard error score: excellent; potential bias score: fair; data source score: excellent.] For total crashes (all crash types and all severities), the CMF is 0.81 with a standard error of 0.06. For fatal and injury crashes (all crash types with injury severity), the CMF is 0.29 with a standard error of 0.07.(10)

Table 5 presents the ranges of CMFs within two standard errors of the point estimates based on the two studies.(7,10) [Note: refer to Example 3 for additional information about standard errors.]

Table 5. Potential range of CMFs for converting signalized intersections to roundabouts.

Crash Type	Crash Severity	Highway Safety Manual(7)	CMF Clearinghouse 4 Star QRS(10)	CMF Clearinghouse 4* and 2 Star** QRS(11)
All	All	0.79-1.19	0.69-0.93	1.78-2.06*
All	Fatal and Injury	0.20-0.60	0.15-0.43	0.52-1.80**

Based on the results from Table 5 (Highway Safety Manual(1,7) and 4-Star QRS(10)), the Team concluded that the conversion of the signalized intersection to a modern two-lane roundabout would very likely, at a 95 percent confidence level, lead to a large reduction in future fatal and injury crashes. The CMFs from the Highway Safety Manual seem to indicate, despite the large reduction in fatal and injury crashes (between 40 and 80 percent), the new roundabout may not result in any change in the overall frequency of crashes (CMF = 1 is included in the range of possible values) or even an increase up to 19 percent representing an increase in non-injury crashes. The CMFs from the 4-Star QRS study found in the CMF Clearinghouse indicate a similar large reduction in fatal and injury crashes (between 57 and 85 percent) but also a reduction in all crashes (between 7 and 31 percent) including non-injury crashes.

When you are searching for the estimate of the safety effect (CMF) of implementing a potential countermeasure, the applicability and reliability of the CMFs may have a decisive role in your decision to implement or not a given countermeasure. CMFs of higher quality with small standard errors and derived from more applicable site conditions will provide more reliable estimates of future crashes after implementation.

In comparison, as also shown in Table 5, the CMF Clearinghouse provides another non-specific (generic) CMF that shows a different safety effect of converting three- or four-leg urban signalized intersections to a modern single- or multi-lane roundabout (traffic volumes 1,900 to 32,900 vehicles/day).(11)As shown in Example 4, though this study gets a 4-Star QRS for total crash CMF, it is a generic, non-specific CMF for total crashes (i.e., data were combined for single- and multi-lane roundabouts and three- and four-legged intersections. The CMF is 1.92±0.07. This same study derived the fatal and injury crash CMF which scored a 2-star quality rating for fatal and injury crashes. The CMF is 1.16±0.32. [2-star Score details: study design score: excellent; sample size score: poor; standard error score: poor; potential bias score: fair; data source score: fair.](11) It is clear this lower quality CMF indicates the conversion to a roundabout could result in more severe crashes; the opposite conclusion reached by other higher quality evaluation studies. Using this lower quality CMF could have led to the conclusion of deferring the implementation of a two-lane roundabout as an effective countermeasure for this signalized intersection.

DATA-DRIVEN BEHAVIOR-BASED METHOD

This section demonstrates the value of using a data-driven behavior-based method to select the most suitable treatments when CMFs are unavailable or unacceptable. This comprehensive and holistic approach supplements the conventional, subjective engineering approach to safety.

When you do not find appropriate CMFs for potential countermeasures you would like to consider, you may find data-driven behavioral studies can provide you with reliable information to support your recommendations.

In the process of identifying potential countermeasures to mitigate crash contributing factors identified during the comprehensive analysis (refer to Example 1), CMFs may not be available for all contemplated countermeasures or available CMFs may not be of sufficient quality. Countermeasures lacking defensible and sound CMFs will need a different approach to evaluate their suitability and potential safety impact. In the absence of acceptable CMFs for a given countermeasure, the application of state-of-the-art human factors in road safety knowledge could provide an alternative data-driven evidence-based method. In these scenarios, the analyst will need to consider the site and road user attributes when evaluating the potential treatment. Module 2 of AASHTOWare Safety Analyst™ provides examples of the holistic approach that guides the analyst through a series of engineering, road safety, and human factors questions and considerations to reach a list of potential countermeasures.

Example 6: Application of Data-Driven Evidence-based Human Factors Road Safety Knowledge

The results of a network screening of an urban jurisdiction indicated a higher than expected frequency and severity of crashes at numerous stop-controlled, three-leg intersections. Subsequently, a multidisciplinary team performed a comprehensive diagnostic investigation, using the five-year crash history to identify target crash types, and using the Haddon Matrix to identify factors contributing to these target crashes. The Team noted the following contributing factors during their diagnosis.

- Most of the severe collisions involved pedestrians or bicycles hit by vehicles approaching the crossing with a major arterial and exiting the minor road.
- Most drivers were turning right though some were turning left.
- The cross-sections of the minor roads are relatively wide (36-ft roadways with 8-ft sidewalks on each side), there are no pavement markings to designate the lanes, and there are typically no parked vehicles.
- There are relatively few driveways and the 85th percentile vehicle speed is 44 mph along the minor roads.

In the process of completing the Haddon Matrix, the Team focused on two factors of note: 1) the vehicle speeds approaching the intersection from the minor road are much higher than the posted speed limit (85^{th} percentile speed is 44 mph compared to the 25 mph posted speed), and 2) the police crash reports documented that several drivers noted they had not seen the bicyclist or pedestrian at all or in time to prevent the collision.

The Team recommended strategies to slow down the approaching vehicles and increase driver expectancy and improve driver visual search for pedestrians and bicyclists. The Team suggested two strategies: raised pedestrian crosswalk at the intersections, and speed humps along the local streets.

The Team searched sources for CMFs for the two strategies:

1. **Raised pedestrian crosswalk:** The Highway Safety Manual does not provide a CMF for a raised pedestrian crosswalk.(1) The Team searched the CMF Clearinghouse for relevant CMFs. The only CMFs found in the CMF Clearinghouse scored a 1-star quality rating; they are CMF = 0.64±0.5 for all crash types that resulted in injury; and CMF = 0.55 ± 0.95 for injury vehicular-pedestrian collisions (in urban and suburban local streets).(12) Given the low quality rating associated with the CMFs, the Team decided to search for other data-driven studies to support their suggestions.
2. **Speed humps:** The installation of speed humps has been evaluated along road segments, and CMFs were found; CMF = 0.6±0.16 for all crash types that resulted in injury (in urban and suburban local streets).(12) The Highway Safety Manual (Table 13-48) presents this CMF. This CMF resulted from a meta-analysis evaluation and scored a 4-star quality rating by the CMF Clearinghouse reviewers. The Team accepted the CMF for speed humps along road segments, but also considered the effect of speed humps on vehicle speeds at the intersection. As such, the Team proceeded to search for additional data-driven information about speed reduction and driver visual search for pedestrian and bicyclists at intersections.

The Team consulted Chapter 2 of the Highway Safety Manual.(1) This chapter introduces elements of human factors related to the interaction between driver, pedestrian, bicyclists, and between the road users and the road design and operations. In Section 2.5, the Highway Safety Manual identifies inadequate visual search as one of the errors contributing to collisions: "*Drivers turning right may concentrate their visual search only on vehicles coming from the left and fail to detect a bicyclist or pedestrian crossing from the right...*" (page 2-14).

The Team continued their information search by consulting the 3rd edition of *Human Factors in Traffic Safety*.(13) Chapter 17 describes visual search in the context of traffic control devices. Two studies mentioned in the chapter researched driver visual search of pedestrians and bicyclists when approaching and turning at intersections. Empirical data and sound data collection of road user behavior supported the results of the research studies. The Team obtained a copy of both publications aiming to review the studies and their findings. If applicable, the findings could provide evidence-based support for countermeasure selection. The following is a description of the findings from these publications:

Robinson et al. observed drivers at three-leg, stop-controlled intersections in an urban area.(14) The visual searches were recorded using video cameras during turning movements. The processing of the field recording data showed most visual searches by the drivers were carried out within a region of 43 feet from the edge of the main road to 6.6 feet into the main road, as drivers were slowing to a stop. Depending of the presence of traffic to the left and right, mean total search times ranged from 7.4 to 10.4 seconds for right turns and 6.7 to 16.9 seconds for left turns, including search time while in motion on the approach. Average individual glances lasted from 1.1 to 2.6 seconds, with the shortest and fewer glances to the right when drivers were making right turns. The search time increased when there was traffic on both directions on the main road. Some drivers making right turns did not look to the right at all, focusing solely on traffic coming from the left, raising the risk of a collision with a pedestrian or bicyclist coming from the right.

Similar to Robinson et al., Summala et al. recorded the empirical field data with two video cameras at three-leg, uncontrolled intersections.(15) The researchers used these data to measure the head movements of the approaching drivers and the speed and distance from the crosswalk. In this first phase of the study, the data confirmed drivers making a right turn focus their attention on the traffic coming from the left, and fail to see approaching bicyclists from the right. Drivers making a right or left turn already started to search traffic coming from the left at approximately 100 ft from the crosswalk. The drivers making a left turn continue searching for traffic approaching from left or right even after entering the main road. Drivers making a right turn stopped searching for traffic approaching from left at approximately 10 ft from the crosswalk, and the few and short glances to the right completely stopped at approximately 20 ft from the crosswalk.

The researchers devised another phase to the study driver behavior after implementation of the countermeasures. The results of the second phase were then compared with the results of the first phase. Countermeasures included speed humps and a raised crosswalk. For each countermeasure, the researchers collected data to measure head movements of approaching drivers and the speed and distance from the crosswalk. The researchers concluded speed humps effectively reduced the speed of approaching drivers and consequently provided drivers more time to focus on each traffic direction. The raised crosswalk increased the number of drivers that glanced to the right. This well-designed, data-driven evaluation demonstrated the two countermeasures modified driver behavior in a positive manner after implementation.

The Team concluded that the evidence based on these data-driven behavioral studies is reliable and applicable to the characteristics of the study locations (i.e., urban, three-leg, stop-controlled intersections). [Note the applicability of results from data-driven behavioral studies is just as important as the applicability of CMFs for estimating potential safety effects.] Given the availability and applicability of data-driven evidence to support the countermeasures, the Team recommended the installation of speed humps and raised crosswalks at the urban, three-leg, stop-controlled intersections. This approach overcame the lack of CMFs for speed humps and raised crosswalks for the specific conditions of urban, three-leg, stop-controlled intersections.

SUMMARY OF METHODS FOR SELECTING COUNTERMEASURES

This guide demonstrates the value of applying more reliable methods in countermeasure selection. More reliable methods result in the identification of targeted, effective, and defensible countermeasures. These methods help to understand how to incorporate crash contributing factors into the countermeasure selection process, identify targeted countermeasures, quantify the safety effects, and consider the range in safety effects. The following is a brief summary of more reliable methods in countermeasure selection.

- **The Haddon Matrix:** The Haddon Matrix is a useful tool to understand crash contributing factors and identify targeted countermeasures for the study location. The first example demonstrates the value of using the Haddon Matrix as part of a comprehensive approach to identify focus crash types, underlying crash contributing factors, and targeted countermeasures.
- **Data-Driven Crash-Based Method:** After identifying potential countermeasures to target the underlying issues, there is a need to assess the safety impact of potential countermeasures. Analysts can use CMFs to quantify and compare the safety effects of multiple potential countermeasures. Examples 2 – 5 demonstrate the value of using CMFs to quantify the safety effects of contemplated countermeasures. The following are specific considerations related to the application of CMFs in countermeasure selection.
    - **Expected versus Observed Crashes:** To apply CMFs, there is a need to estimate future crashes without treatment (i.e., the do-nothing alternative). The second example demonstrates the value of using the EB method to develop a more reliable estimate of future crashes without treatment compared to historical crash records only. Specifically, the EB method combines historical observed crashes with predicted crashes from an SPF to overcome issues related to the variability in crashes and traffic volume over time.
    - **Standard Errors of CMFs:** CMFs provide a point estimate of the safety effects of a countermeasure. The third example demonstrates the value of incorporating the standard error of the CMF to understand the potential range in safety effects.
    - **Applicability of CMFs:** Given multiple CMFs for a specific countermeasure, it is more appropriate to use an applicable CMF compared to a less applicable, or generic CMF. The fourth example demonstrates the value of using more applicable CMFs to estimate the safety effect of potential countermeasures.
    - **Reliability of CMFs:** Given multiple CMFs for a countermeasure, it is more appropriate to use a higher quality CMF compared to a lower quality CMF. The fifth example demonstrates the value of using more reliable CMFs to estimate the effect of potential countermeasures.
- **Data-Driven Behavior-Based Method:** The data-driven behavior-based method is useful to select the most suitable treatments when applicable CMFs are not available. This is an alternative to the conventional, subjective engineering approach to safety. The sixth example demonstrates the value of a comprehensive and holistic approach when CMFs are not available for the potential countermeasure or specific site conditions of interest.

In summary, the use of more reliable countermeasure selection methods will lead to the identification and selection of targeted, effective, and defensible countermeasures to mitigate specific safety issues at given sites.

4. DATA REQUIREMENTS FOR COUNTERMEASURE SELECTION

The following is a brief overview of the data requirements for countermeasure selection using the more reliable state-of-the-art methods described in this information guide.

- **Crash Data**: three to five years of police crash reports for the study location. Review of individual crash reports to identify contributing factors as reported by the police. This information supports the completion of the Haddon Matrix for each target crash type.
- **Traffic Volume Data**: three to five years of traffic volume data for the study location, as well as forecasted traffic volumes for the projected service life of contemplated countermeasures. As a minimum, there is a need for at least one historical estimate and one future estimate that represents a potential implementation year.
- **Roadway Data (Site Conditions)**: From the diagnosis step, carry forward the observations from site visits (field investigations), including traffic operations, design elements, adjacent land use, driver demographics, and other elements. This information supports the completion of the Haddon Matrix for each target crash type. A preliminary office review of the site using aerial images and video or photo logs can support a more efficient field investigation.
- **SPFs**: Obtain appropriate SPFs for the study location. SPFs may be available for a given jurisdiction or borrowed from another jurisdiction with sites of similar conditions to the study location. In either case, there is a need to calibrate SPFs using local data to reflect local and current conditions. [Note analysts may use FHWA's calibration tool, The Calibrator, and related user guide to calibrate SPFs.]
- **Crash Costs**: To complete an economic appraisal, there is a need for average crash costs by crash type and severity level. [Note in the absence of agency-specific crash costs, analysts may refer to FHWA's Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries.](5)
- **Countermeasure Details**: For each potential countermeasure, there is a need to identify the expected safety effects post implementation (for the specific site conditions) and reported contraindications (e.g., noise of rumble strips near residential developments). The Highway Safety Manual and CMF Clearinghouse provide CMFs and associated standard errors for various countermeasures. These sources indicate the applicability of the CMFs with respect to site condition, crash type, and crash severity.
- **Transport Research International Documentation (TRID)**: Access TRID for a centralized searchable database of literature related to road safety. This is useful to identify full text reports or publications related to contributing factors or countermeasures of interest. For example, analysts may search for CMF-related publications to understand the context of the original study. When applicable, high-quality CMFs are unavailable, analysts may search for data-driven human factors research in road safety as an alternative evidence-based approach to countermeasure selection.

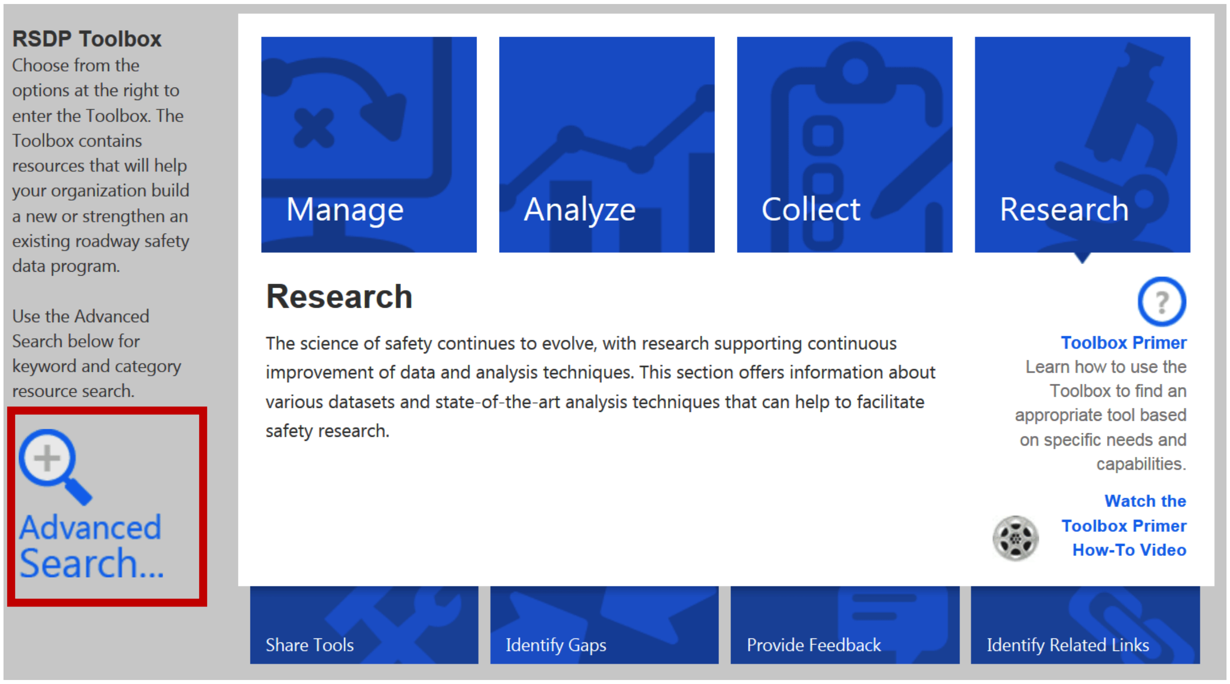
5. TOOLS AND RESOURCES FOR COUNTERMEASURE SELECTION

Tools and resources are available to support countermeasure selection, including guides and software. Some guides provide a discussion of the countermeasure selection process, while other tools relate to specific components of the process. For example, tools such as the National Cooperative Highway Research Program (NCHRP) Report 500 series can help users identify appropriate countermeasures for a given safety issue. The FHWA CMF Clearinghouse and related resources can help users identify and apply CMFs.

The FHWA Roadway Safety Data and Analysis Toolbox is a web-based repository of safety data and analysis tools. Use the Toolbox to identify an appropriate tool for your countermeasure selection needs. A Primer is available to understand the overall scope and functionality of the Toolbox as well as the roles, responsibilities, and tasks supported by tools in the Toolbox.

USING THE ROADWAY SAFETY DATA AND ANALYSIS TOOLBOX

There are two primary options for searching the Toolbox. The first is a predefined query using the four large icons in the upper right of Figure 30 (Manage, Analyze, Collect, and Research). The second is an advanced search option where users can search keywords and apply filters to customize their search as shown in the lower left of Figure 30.



RSDP Toolbox

Choose from the options at the right to enter the Toolbox. The Toolbox contains resources that will help your organization build a new or strengthen an existing roadway safety data program.

Use the Advanced Search below for keyword and category resource search.

Research

The science of safety continues to evolve, with research supporting continuous improvement of data and analysis techniques. This section offers information about various datasets and state-of-the-art analysis techniques that can help to facilitate safety research.

Toolbox Primer

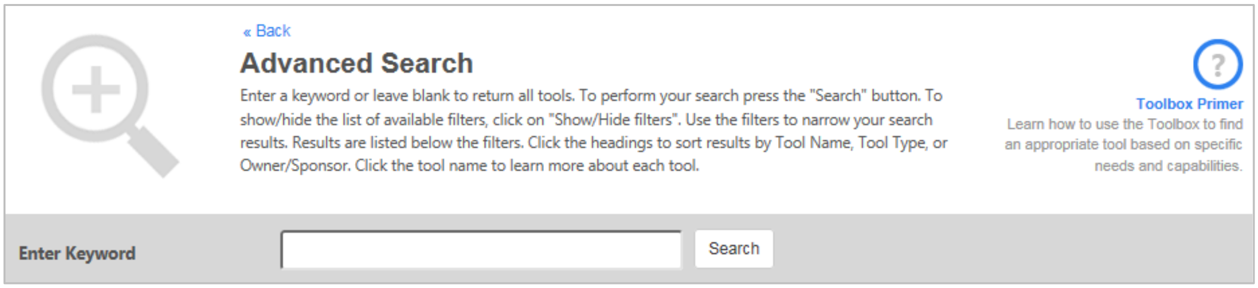
Learn how to use the Toolbox to find an appropriate tool based on specific needs and capabilities.

Watch the Toolbox Primer How-To Video

Figure 30. Graphic. Screenshot of Roadway Safety Data and Analysis Toolbox.

The following is a brief demonstration of the stepwise process to identify an appropriate tool to support countermeasure selection.

1. Click the ‘Advanced Search’ icon, highlighted in the lower left of Figure 30.
2. From the advanced search page (Figure 31), leave the keyword blank and click the search button. This returns a list of all tools in the Toolbox.



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Advanced Search

Enter a keyword or leave blank to return all tools. To perform your search press the "Search" button. To show/hide the list of available filters, click on "Show/Hide filters". Use the filters to narrow your search results. Results are listed below the filters. Click the headings to sort results by Tool Name, Tool Type, or Owner/Sponsor. Click the tool name to learn more about each tool.

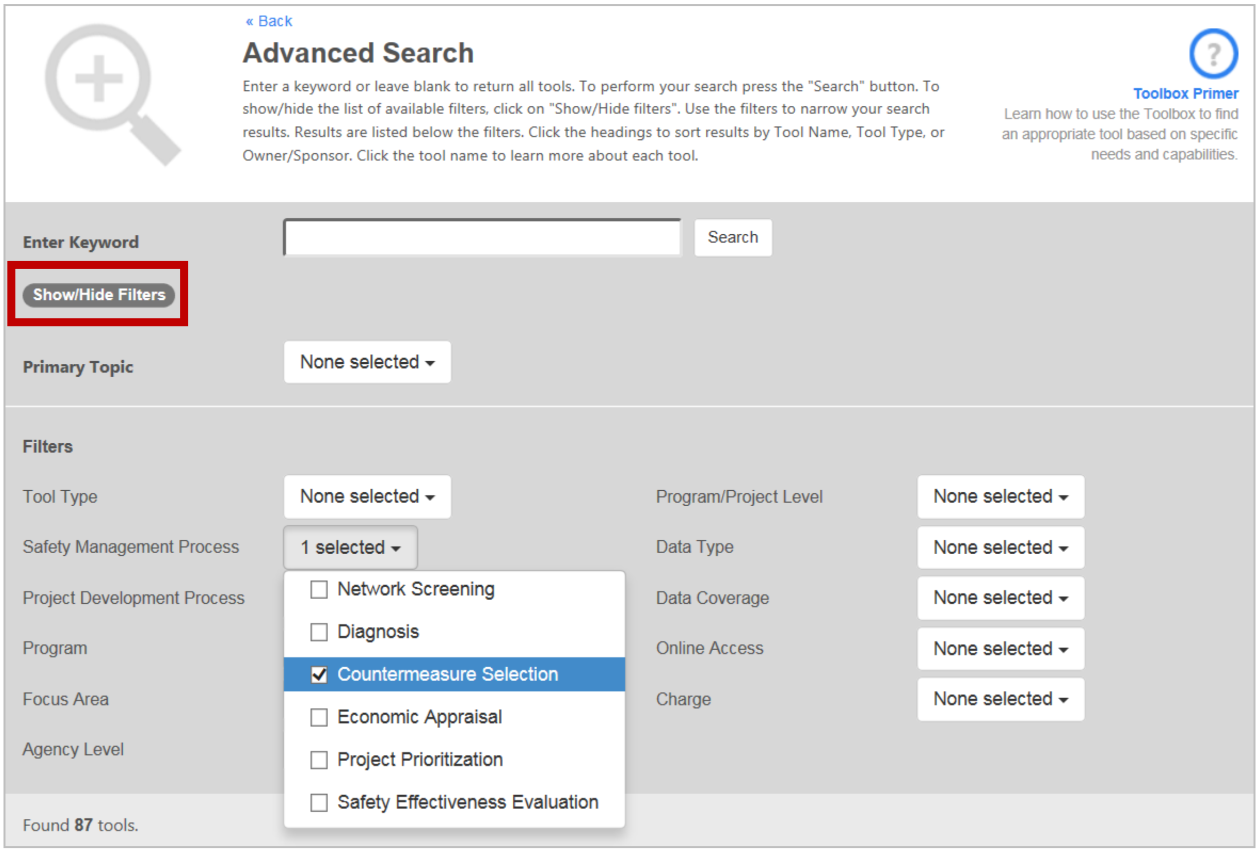
Toolbox Primer

Learn how to use the Toolbox to find an appropriate tool based on specific needs and capabilities.

Enter Keyword

Figure 31. Graphic. Screenshot of advanced search feature.

Click the 'Show/Hide Filters' button, highlighted in the upper left of Figure 32. This reveals a list of filters to refine the general search. Use the 'Safety Management Process' filter to select 'Countermeasure Selection' as the primary area of interest as shown in Figure 32. Apply additional filters as needed to refine the results. For example, apply the 'Tool Type' filter to narrow the list of tools to application guides, information guides, software, information sources, or databases.



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Advanced Search

Enter a keyword or leave blank to return all tools. To perform your search press the "Search" button. To show/hide the list of available filters, click on "Show/Hide filters". Use the filters to narrow your search results. Results are listed below the filters. Click the headings to sort results by Tool Name, Tool Type, or Owner/Sponsor. Click the tool name to learn more about each tool.

Toolbox Primer

Learn how to use the Toolbox to find an appropriate tool based on specific needs and capabilities.

Enter Keyword

Primary Topic: None selected

Filters

Tool Type	None selected	Program/Project Level	None selected
Safety Management Process	1 selected	Data Type	None selected
Project Development Process		Data Coverage	None selected
Program		Online Access	None selected
Focus Area		Charge	None selected
Agency Level			

☐ Network Screening
☐ Diagnosis
☑ Countermeasure Selection
☐ Economic Appraisal
☐ Project Prioritization
☐ Safety Effectiveness Evaluation

Found **87** tools.

Figure 32. Graphic. Screenshot of filter options from advanced search page.

Using the stepwise process described in this section, the Toolbox returns guides such as Proven Safety Countermeasures, Countermeasures That Work, CMFs in Practice, and Human Factors Guidelines for Road Systems. The CMFs in Practice series describes the use of CMFs in specific aspects of the project development process. Other related tools from the Toolbox include the CMF Clearinghouse and AASHTOWare Safety Analyst™.

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For More Information:

Stuart Thompson
Stuart.Thompson@dot.gov
202-366-8090

Federal Highway Administration
Office of Safety
1200 New Jersey Avenue SE
Washington, DC 20590
http://safety.fhwa.dot.gov/

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