

Report No. UT-10.12c

TRANSPORTATION SAFETY DATA AND ANALYSIS Volume 3: Framework for Highway Safety Mitigation and Workforce Development

Prepared For:

Utah Department of Transportation
Traffic and Safety, Research Divisions

Submitted By:

Brigham Young University
Dept. of Civil & Environmental Engineering

Authored By:

Grant G. Schultz, Ph.D., P.E., PTOE
Associate Professor

Steven C. Dudley, EIT
Graduate Research Assistant

Mitsuru Saito, Ph.D., P.E.
Professor

May 2011

INSIDE COVER

Report No. UT-10.12c

**TRANSPORTATION SAFETY
DATA AND ANALYSIS
Volume 3: Framework for Highway
Safety Mitigation and Workforce
Development**

Prepared For:

Utah Department of Transportation
Traffic and Safety, Research Divisions

Submitted By:

Brigham Young University
Department of Civil & Environmental Engineering

Authored By:

Grant G. Schultz, Ph.D., P.E., PTOE
Associate Professor

Steven C. Dudley
Graduate Research Assistant

Mitsuru Saito, Ph.D., P.E.
Professor

May 2011

THIS PAGE INTENTIONALLY LEFT BLANK

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation and the US Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

This report is protected under 23 USC 409.

THIS PAGE INTENTIONALLY LEFT BLANK

UDOT RESEARCH REPORT ABSTRACT

1. Report No. UT-10.12c		2. Government Accession No.	3. Recipients Catalog No.
4. Title and Subtitle TRANSPORTATION SAFETY DATA AND ANALYSIS Volume 3: Framework for Highway Safety Mitigation and Workforce Development		5. Report Date May 2011	
		6. Performing Organization Code:	
7. Author(s) Grant G. Schultz, Ph.D., P.E., PTOE Steven C. Dudley Mitsuru Saito, Ph.D., P.E.		8. Performing Organization Report No.	
9. Performing Organization Name and Address: Brigham Young University Department of Civil & Environmental Eng. Provo, UT 84602		10. Work Unit No. 5304815D	
		11. Contract No. 10-9103	
12. Sponsoring Agency Name and Address: Utah Department of Transportation Research Division 4501 South 2700 West Salt Lake City, UT 84114-8410		13. Type of Report and Period Covered September 2009 – May 2011	
		14. Sponsoring Agency Code PIC No. UT09.602	
15. Supplementary Notes: Prepared in cooperation with the Utah Department of Transportation			
16. Abstract Safety has always been an important component in the planning, design, and operation of highways. In an effort to reduce crashes occurring on highway facilities, the Safe, Accountable, Flexible, and Efficient Transportation Equity Act - A Legacy for Users of 2005 established a new Highway Safety Improvement Program that encourages the integration of safety into the decision-making process and facilitates the expenditure of funds for highway safety improvement. A framework for highway safety mitigation is outlined in this report that provides a logical and comprehensive context within which efforts to improve highway safety can be made. This framework has been developed around the Roadway Safety Management Process contained in the Highway Safety Manual and has six primary steps: 1) Network Screening; 2) Diagnosis; 3) Countermeasure Selection; 4) Economic Appraisal; 5) Project Prioritization; and 6) Effectiveness Evaluation. The application of this framework and the predictive methods of safety analysis it entails requires familiarity with the latest advances in highway safety research and practices. Therefore, recommendations on safety workforce development are presented along with a summary of possible training resources. The framework for highway safety mitigation and safety workforce development recommendations provided in this report are part of an ongoing effort to improve highway safety across the state of Utah and will play an important role in training the next generation of safety experts that will be able to meet the highway safety needs of tomorrow.			
17. Key Words Transportation safety, Bayesian models, safety mitigation, safety workforce development, highway safety training		18. Distribution Statement Available from: Utah Department of Transportation Research Division Box 148410 Salt Lake City, Utah 84114-8410 Brigham Young University Department of Civil & Environmental Engineering 368 Clyde Building Provo, Utah 84602	
19. Security Classification (Of this report) Unclassified	20. Security Classification (Of this page) Unclassified	21. No. of Pages 88	22. Price

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

This research was made possible with funding from the Utah Department of Transportation (UDOT) and Brigham Young University (BYU). Special thanks to the several professionals at UDOT and BYU who played key roles as members of the Technical Advisory Committee (TAC). The members of the committee were:

- Robert Hull – UDOT Traffic & Safety;
- W. Scott Jones – UDOT Traffic & Safety;
- David Stevens – UDOT Research Division;
- Tim Taylor – WCEC/UDOT Traffic & Safety;
- Members of the UDOT Traffic & Safety Committee;
- Grant Schultz – BYU Associate Professor;
- Mitsuru Saito – BYU Professor;
- Steven C. Dudley – BYU Graduate Student;
- Brad K. Brimley – BYU Graduate Student;
- Andrew N. Olsen – BYU Graduate Student; and
- C. Shane Reese – BYU Professor.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

UDOT RESEARCH REPORT ABSTRACT	v
LIST OF TABLES	xiii
LIST OF FIGURES	xv
EXECUTIVE SUMMARY	ES-1
1 INTRODUCTION	1
1.1 Background.....	1
1.2 Objectives	2
1.3 Organization.....	2
2 LITERATURE REVIEW	5
2.1 The Integration of Safety in Transportation Decision Making.....	5
2.2 Fundamentals of Safety Analysis and Mitigation.....	6
2.2.1 Definition of Roadway Safety	6
2.2.2 Crashes as a Measure of Safety	7
2.2.3 Factors Contributing to Crashes.....	7
2.2.4 Crash Severity	8
2.2.5 Nature of Crashes.....	9
2.3 Methods of Safety Analysis.....	11
2.3.1 Traditional Descriptive Analysis	11
2.3.2 Predictive Analysis	12
2.4 HSM Roadway Safety Management Process	14
2.5 Chapter Summary	14
3 FRAMEWORK FOR HIGHWAY SAFETY MITIGATION	17
3.1 Network Screening	17
3.1.1 Establish Focus	18
3.1.2 Identify the Network and Establish Reference Populations.....	19

3.1.3	Select Performance Measures	19
3.1.4	Select Screening Method	20
3.1.5	Screen and Evaluate Results	24
3.1.6	Application of Jurisdiction-Specific Crash Prediction Models (from Volume 2 report).....	24
3.2	Diagnosis	26
3.2.1	Safety Data.....	26
3.2.2	Supporting Documentation	27
3.2.3	Field Conditions.....	29
3.3	Countermeasure Selection	30
3.3.1	Identify Factors Contributing to Crashes	30
3.3.2	Identify Potential Countermeasures	32
3.3.3	Select Preferred Treatment based on Economic Appraisal.....	32
3.4	Economic Appraisal.....	33
3.4.1	Assess Expected Project Benefits	33
3.4.2	Estimate Project Cost.....	35
3.4.3	Apply Economic Evaluation Methods	36
3.5	Project Prioritization	38
3.5.1	Ranking Procedures	38
3.5.2	Optimization Methods	39
3.5.3	Multi-objective allocation	39
3.6	Safety Effectiveness Evaluation	40
3.6.1	Types of Effectiveness Evaluation Studies.....	40
3.6.2	Study Designs	41
3.6.3	Framework for Safety Effectiveness Evaluation	42
3.6.4	Development of Crash Modification Factors.....	44
3.6.5	Economic Appraisal of Safety Treatments	44
3.6.6	Hierarchical Bayes Effectiveness Evaluation (from Volume 1 report)	45
3.7	Chapter Summary	47
4	SAFETY WORKFORCE DEVELOPMENT.....	49
4.1	Current State of Highway Safety Training Resources.....	49

4.2	Considerations of Workforce Development	50
4.3	Possible Training Opportunities	52
4.3.1	FHWA Resource Center HSM Webinar Series	52
4.3.2	NHI Safety Training Courses.....	53
4.3.3	ITE Safety Training Resources	56
4.4	Chapter Summary	57
5	CONCLUSION.....	59
5.1	Summary and Conclusions	59
5.2	Suggestions for Future Research	61
	REFERENCES	63
	LIST OF ACRONYMS	67

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 3-1. Summary of Data Needs of Performance Measures.....	21
Table 3-2. Stability of Performance Measures	22
Table 3-3. Recommended Screening Methods for Network Elements.....	22
Table 3-4. Example Haddon Matrix for Rear-End Crash	31
Table 3-5. UDOT and FHWA Societal Crash Costs by Severity	35
Table 4-1. Five Forms of Learning	51
Table 4-2. HSM Webinars offered by FHWA Resource Center	53
Table 4-3. Recommended HSM Courses from NHI.....	55
Table 4-4. ITE HSM Predictive Method Applications Webinar Series.....	56

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure ES-1. Framework for highway safety mitigation.....	ES-1
Figure 2-1. Contributing factors to vehicle crashes	8
Figure 2-2. Variation in short-term observed crash frequency	10
Figure 2-3. Regression-to-the-Mean (RTM) Bias	10
Figure 3-1. Framework for highway safety mitigation.....	18
Figure 3-2. ‘Hot spot’ analysis using a hierarchal Bayesian model	25
Figure 3-3. Example graphical summary of intersection crashes	28
Figure 3-4. Example collision diagram.....	28
Figure 3-5. Example condition diagram	29
Figure 3-6. Severe crashes for all raised median study sites	46
Figure 3-7. Distribution of differences of severe crashes for all raised median study sites	46
Figure 5-1. Framework for highway safety mitigation.....	60

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Safety has always been an important component in the planning, design, and operation of highways. In an effort to reduce crashes occurring on highway facilities, the Safe, Accountable, Flexible, and Efficient Transportation Equity Act - A Legacy for Users of 2005 established a new Highway Safety Improvement Program that encourages the integration of safety into the decision-making process and facilitates the expenditure of funds for highway safety improvement. A framework for safety mitigation is outlined in this report that incorporates predictive methods of highway safety analysis, which allows transportation officials to proactively improve the safety of the transportation system. This framework, shown in Figure ES-1, has been developed around the Roadway Safety Management Process contained in the Highway Safety Manual and has six primary steps: 1) Network Screening; 2) Diagnosis; 3) Countermeasure Selection; 4) Economic Appraisal; 5) Project Prioritization; and 6) Effectiveness Evaluation.

This framework for highway safety mitigation provides a logical and comprehensive context within which efforts to improve highway safety can be made. First, safety ‘hot spots’ in a road network may be identified by comparing the actual safety performance with the expected performance of a site. If the actual safety is significantly below the expected safety, the site is considered a ‘hot spot’ and examined more closely to determine cost-effective countermeasures that could be implemented. The review of past safety data, supporting documents, and the geometric and operational characteristics of a site can lead to an understanding of factors that could be contributing to crashes. Once these crash patterns are understood, potential countermeasures that address safety concerns can be identified, evaluated for economic viability, and compared to find a preferred alternative for implementation. The last objective of this framework for safety mitigation is to improve future decision making and policy through the evaluation of implemented highway safety improvement projects. Projects found beneficial to highway safety should be considered in future safety improvement efforts. Effective

countermeasures with a high benefit-to-cost ratio should even be considered for a policy of state-wide implementation. As the Utah Department of Transportation uses this framework for safety mitigation, they can maximize the benefits resulting from highway safety investment.

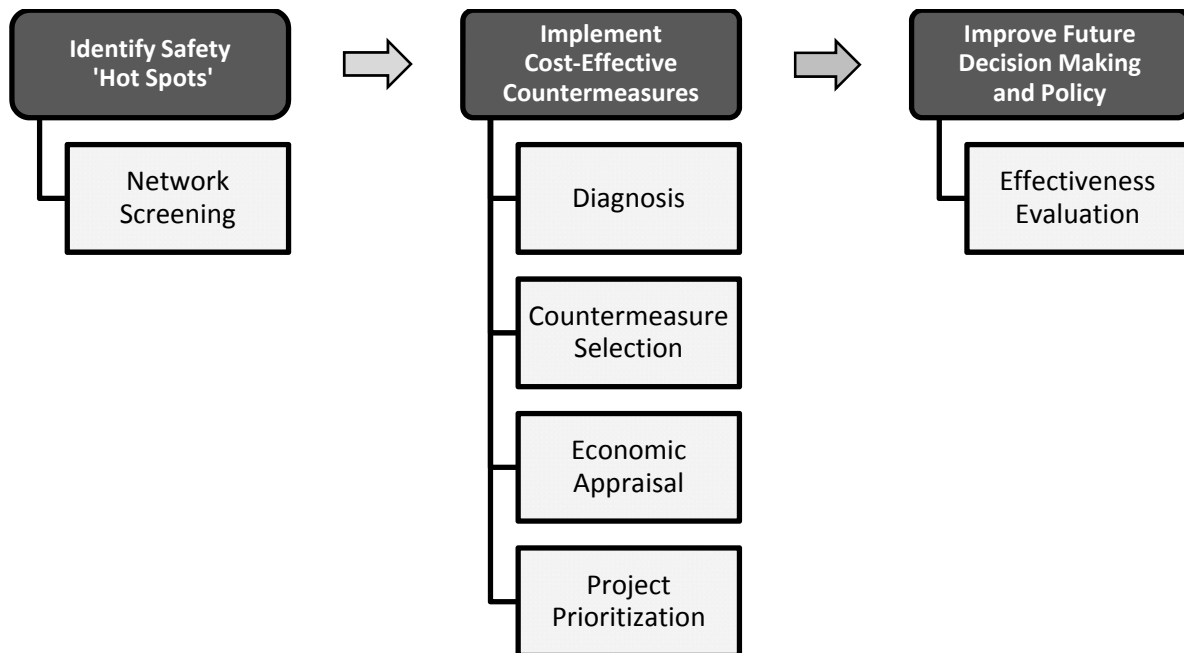


Figure ES-1. Framework for highway safety mitigation.

The application of this framework and the predictive methods of safety analysis it entails requires familiarity with the latest advances in highway safety research and practices. Therefore, recommendations on safety workforce development are presented in this report along with a summary of possible resources for highway safety training, including those that focus on state-of-the-art safety analysis methods and encourage the integration of safety into transportation decision making.

The framework for highway safety mitigation and safety workforce development recommendations provided in this report are part of an ongoing effort to improve highway safety across the state of Utah and will play an important role in training the next generation of safety experts that will be able to meet the highway safety needs of tomorrow.

1 INTRODUCTION

Although safety has long been important in the transportation decision making process, recent changes in transportation policy call for safety to play an increasingly significant role in the way highways are planned, designed, operated, and maintained. The Safe, Accountable, Flexible, and Efficient Transportation Equity Act - A Legacy for Users (SAFETEA-LU) established a new Highway Safety Improvement Program (HSIP) that encourages state-level engineering efforts to improve safety on the nation's highways (FHWA 2005). In response to these policy changes, the Utah Department of Transportation (UDOT) developed and maintains a Strategic Highway Safety Plan (SHSP) and continues to improve in its ability to identify highway safety needs through the state.

1.1 Background

In 2010, the American Association of State Highway and Transportation Officials (AASHTO) published a new transportation safety guide, the Highway Safety Manual (HSM). The HSM was developed in response to the realization that there was a lack of a single authoritative document to use for estimating safety impacts (AASHTO 2010). The HSM represents 10 years of research overseen by the Transportation Research Board (TRB) and sponsored by AASHTO, the Federal Highway Administration (FHWA), and the Institute of Transportation Engineers (ITE). The HSM incorporates many recent advances in highway safety analysis that allows transportation officials to more reliably identify sites with safety needs and implement measures necessary to mitigate safety concerns (AASHTO 2010).

Recent changes in transportation policy and advances in highway safety analysis have necessitated changes in the way highway safety needs are identified and mitigated. A framework for safety mitigation that integrates new approaches for evaluating safety can help transportation officials make better decisions on where to invest limited highway improvement funds.

1.2 Objectives

The objective of this research was to present an overall highway safety mitigation process for the state of Utah. A framework for safety mitigation will be outlined including a discussion of both traditional approaches and newer, more advanced approaches to safety analysis. Possible safety training opportunities and resources will be presented with recommendations on developing a workforce development program to help transportation professionals in Utah further incorporate safety into all aspects of the transportation profession. Additionally, possibilities for future research will be presented and discussed.

This report is Volume 3 of a three volume research report series. Volume 1, titled *Analyzing the Effectiveness of Safety Measures using Bayesian Methods*, discussed before/after safety studies and presented a Bayesian approach to conducting highway safety effectiveness evaluation (Schultz et al. 2010). This new approach was demonstrated on selected locations where raised medians and cable barrier systems have been installed on Utah roadways. Volume 2, titled *Calibration of the Highway Safety Manual and Development of New Safety Performance Functions*, discussed calibrating HSM crash prediction methods and the development of new jurisdiction-specific crash prediction models for Utah rural two-lane two-way roads (Saito et al. 2011). This report provides context for the methods presented in the Volume 1 and Volume 2 reports and allows them to be more easily implemented.

1.3 Organization

This report is organized into the following chapters: 1) Introduction; 2) Literature Review; 3) Framework for Highway Safety Mitigation; 4) Safety Workforce Development; and 5) Conclusions. A References section and a List of Acronyms follow the indicated chapters.

Chapter 2 is a literature review discussing the need for the integration of safety into the transportation decision making process and the fundamental concepts of highway safety mitigation, including defining safety and how it is measured. A brief discussion of safety analysis methods is also presented wherein traditional descriptive and newer predictive methods of analysis are discussed. Additionally, the HSM Roadway Safety Management Process is introduced.

Chapter 3 presents a framework for highway safety mitigation based on the HSM Roadway Safety Management Process. A summary of each component of the safety mitigation process, including network screening, diagnosis, countermeasure selection, economic appraisal, project prioritization, and safety effectiveness evaluation is provided. Methods and findings of Volume 1 and Volume 2 of this report series are discussed in the appropriate steps of the safety mitigation process.

Chapter 4 discusses the need for safety workforce development to help transportation professionals in Utah effectively apply advanced safety methods and tools to the project development process. In this chapter, important considerations on developing a safety workforce development program along with possible safety training opportunities are presented.

Chapter 5 provides the conclusions of the research as well as recommendations for future research possibilities.

A list of acronyms used within this report is provided at the end of this report.

THIS PAGE INTENTIONALLY LEFT BLANK

2 LITERATURE REVIEW

A literature review has been performed on concepts related to highway safety mitigation. This chapter gives the reader background on the increasing significance of the integration of safety in the transportation decision making process; fundamentals of safety analysis and mitigation; methods of safety analysis; and the HSM Roadway Safety Management Process. A summary of the chapter is also provided.

2.1 The Integration of Safety in Transportation Decision Making

Safety has long been considered in the transportation decision-making process. Past efforts to improve highway safety have made a difference but more can still be done. Increasing emphasis on safety in transportation policy, along with advances in highway safety analysis, will ensure that highway safety continues to play a crucial role in the way highway facilities are planned, designed, operated, and maintained long into the future.

In 2005, SAFETEA-LU placed increased emphasis on safety in transportation policy. In this legislation, the HSIP was upgraded to a core federal-aid program, which nearly doubled the funds available for transportation safety investment (FHWA 2005). The purpose of the HSIP is to reduce the number of fatal and serious/injury crashes through state-level engineering methods. In an effort to meet this objective, the HSIP requires the department of transportation (DOT) from each state to develop a SHSP focused on reducing vehicle-related fatalities and injuries through implementing data-driven safety improvement projects (FHWA 2005).

For an infrastructure project to qualify for HSIP funding, the project must be on a public roadway, be in a location with a correctable crash history, be expected to reduce crashes at or near the project location, and have a positive estimated benefit-cost ratio (UDOT 2011b). The FHWA requires each state DOT to submit an annual *HSIP Report* detailing how HSIP money is

being used as well as a separate annual *5 Percent Report* discussing safety mitigation efforts at the top 5 percent of highway locations exhibiting severe safety needs (FHWA 2005).

In order to fulfill mandates outlined in the HSIP, state transportation officials need effective tools and methods to make optimal decisions regarding highway safety improvement. In the past, it was often assumed that a transportation entity was safe if it met appropriate design standards. However, design standards are not typically evaluated specifically for their effect on safety. Safety is becoming more and more science-driven, focusing more on data and analysis (Herbel et al. 2010).

Research efforts in highway safety over the last decade have culminated in the development of the HSM, a guide that incorporates state-of-the-art analytical techniques to evaluate and improve safety. Traditional safety evaluation relied on descriptive analysis, which involves summarizing and quantifying historic crash data. However, advances in safety evaluation are creating a shift towards using quantitative predictive analysis more often. Quantitative predictive analysis is used to determine the expected number and severity of crashes at sites of interest under multiple time periods or conditions (AASHTO 2010). In addition to allowing descriptive methods to be more effectively used, the HSM provides information and tools that can help state transportation officials to utilize quantitative predictive analysis in their efforts to improve highway safety.

2.2 Fundamentals of Safety Analysis and Mitigation

An understanding of general principles and practices of transportation safety is needed to better understand the highway safety mitigation process. The following subsections briefly discuss some of the basic concepts involved in highway safety analysis and mitigation including a definition of roadway safety, crashes as a measure of safety, factors contributing to crashes, crash severity, and the nature of crashes. A more detailed discussion of these concepts can be found in the *HSM* (AASHTO 2010) and in the *HSIP Manual* (Herbel et al. 2010).

2.2.1 Definition of Roadway Safety

Roadway safety may be defined in multiple ways. Subjective safety is the perception of how safe a transportation system ‘feels’ to an observer. Objective safety is how safe a

transportation system ‘is’ based on a quantitative measure of safety, such as crash frequency or crash severity. Whereas subjective safety varies from observer to observer, objective safety is quantifiable and independent of the observer. Safety, as defined in the HSM, is “the number of crashes, by severity, expected to occur on the entity per unit of time” (AASHTO 2010, p. G-12).

2.2.2 Crashes as a Measure of Safety

Crashes are a widely used and quantifiable measure that determines the safety of an entity. A crash can be defined as “a set of events that result in injury or property damage due to the collision of at least one motorized vehicle and may involve collision with another motorized vehicle, a bicyclist, a pedestrian, or an object” (AASHTO 2010, p. 3-3). Although other types of collisions may occur, only collisions involving motorized vehicles are used to measure safety in this report.

Although crashes are the fundamental unit of highway safety, crash frequencies are often useful in crash analysis. A crash frequency is the number of crashes that occur in a specific period of time. Equation 2-1 shows how crash frequency is calculated.

$$\text{Crash Frequency} = \frac{\text{Number of Crashes}}{\text{Period of Time}} \quad (2-1)$$

2.2.3 Factors Contributing to Crashes

An important aspect of highway safety mitigation is understanding factors that contribute to crashes. Most crashes cannot be attributed to one singular causal event, but rather to a combination of factors and events that led up to the crash. The factors contributing to a crash generally fall into three categories – human, vehicle, and roadway/environment. Human factors are attributes of the driver that may contribute to a crash. These attributes include such things as age, judgment, driver skill, attention, fatigue, experience, and sobriety. Vehicles factors include aspects of the design, manufacture, and maintenance of vehicles involved in a crash. Energy adsorption, restraint devices, airbag systems, manufacturing defects, and maintenance conditions can all influence the likelihood and severity of a crash. Roadway and environmental factors include the physical layout and conditions of the roadway, weather, and visibility.

Research conducted in 1979 examined factors contributing to crashes and determined the relative proportion that human, vehicle, and roadway factors each contributed to vehicle crashes (AASHTO 2010; Treat et al. 1979). Figure 2-1 shows a summary of this research. Note that the percentages in Figure 2-1 do not add up to 100 percent as multiple types of factors may contribute to a given crash. For example, poorly maintained brakes, low roadway surface friction, and slow driver response time may all contribute to a crash caused by the failure of a vehicle to stop.

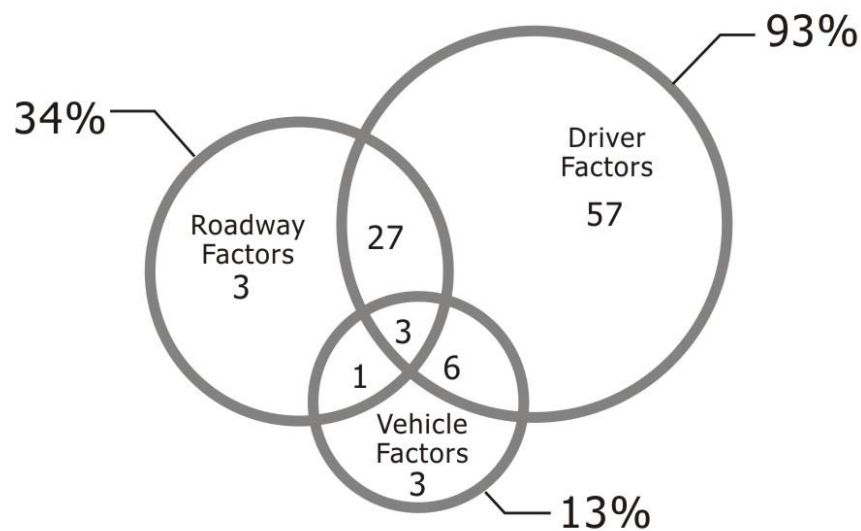


Figure 2-1. Contributing factors to vehicle crashes (AASHTO 2010; Treat et al. 1979).

Although environmental conditions are usually out of the control of transportation professionals, roadway characteristics such as the geometric alignment, cross-section, pavement conditions, and traffic control devices can be modified to influence crash frequency and crash severity.

2.2.4 Crash Severity

Not all crashes are of the same consequence. Some crashes result in only minor injury or property damage. Yet other crashes result in the severe injury or even death of those involved. Motor vehicle crashes are categorized into five categories which in decreasing order of severity are: fatal, incapacitating injury, non-incapacitating evident injury, possible injury, and non-injury

(NSC 2007). The severity of the crash is based on the highest level of injury sustained by any persons involved. The KABCO scale, a system used by law enforcement officers to code crashes, quantifies the severity of a crash (NHTSA 2008). A letter is assigned from the KABCO scale designating the level of severity with “K” being the most severe and “O” being the least severe. The level of severity of a crash is determined and recorded by law enforcement at the scene of the crash.

2.2.5 Nature of Crashes

Crashes are events that are both rare and random. “Rare” indicates that crashes represent only a small proportion of all events and movements that occur in a transportation system. “Random” indicates that crashes are the result of a combination of many factors and hard to accurately predict. The random nature of crashes produces variability in the crash frequency at a given site from year to year (AASHTO 2010).

Changes in crash frequencies between two periods or conditions should be compared using long-term estimates of crash frequency, otherwise known as the expected average crash frequency, to minimize the effect of fluctuations in crash frequency. However, reliable long-term estimates of crash frequency are hard to obtain. Since it is difficult to know if a short-term crash frequency represents a typically high, average, or low crash frequency at a site, it cannot reliably estimate the long-term crash frequency. Using data from a longer term can also produce unreliable estimates of the long-term crash frequency as the characteristics of the site will likely change during that time. The variation of observed short-term averages illustrated in Figure 2-2 demonstrates how short-term averages fail to reliably estimate the long-term crash frequency. Both short-term averages in Figure 2-2 differ significantly from the long-term average (AASHTO 2010).

The tendency of the crash frequency at a given site to fluctuate up and down around an expected average crash frequency is known as regression to the mean (RTM) and presents challenges in crash analysis (AASHTO 2010). RTM is the phenomenon that there is a high probability that a period with relatively high crash frequency will be followed by one with a lower crash frequency. Due to RTM, the true effectiveness of a highway safety improvement cannot be readily assessed (Hauer 1997). If a highway safety improvement is implemented due to a site having an unusually high crash frequency, a simple analysis might indicate that the

improvement is more effective than it really is. This phenomenon is known as RTM bias. Figure 2-3 illustrates how RTM bias may occur if short-term averages from the before and after period are compared directly, resulting in a perceived effectiveness greater than the actual effectiveness.

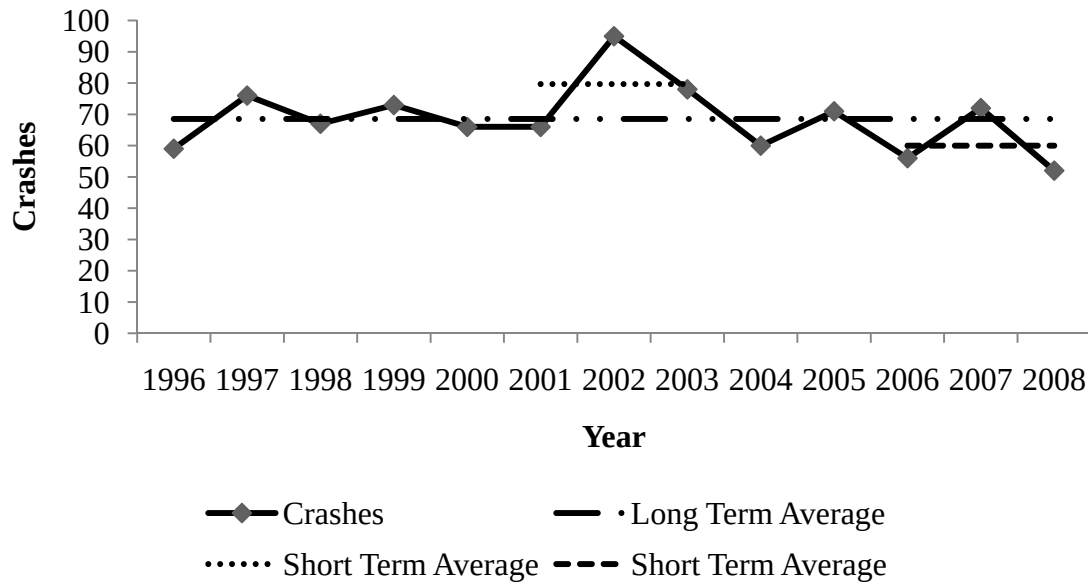


Figure 2-2. Variation in short-term observed crash frequency (adapted from AASHTO 2010).

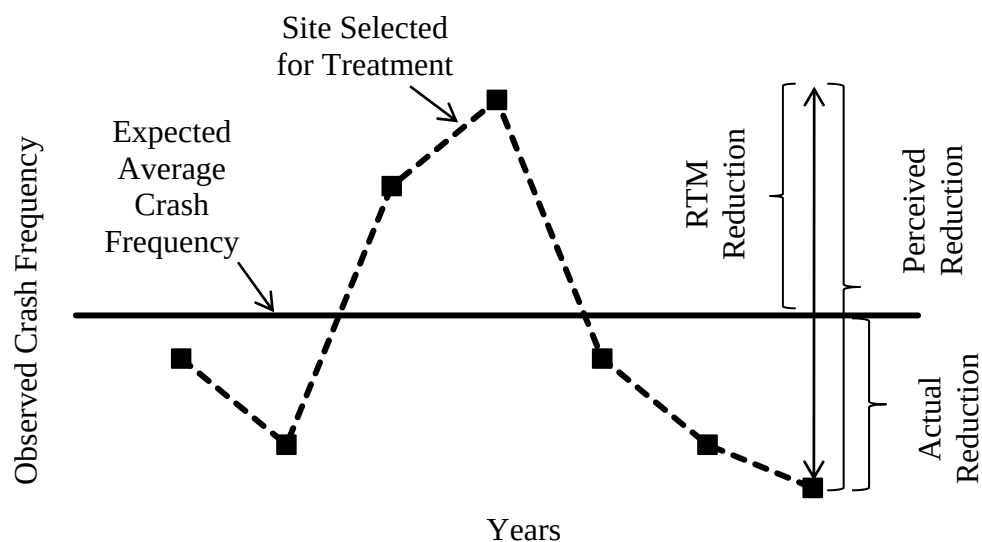


Figure 2-3. Regression-to-the-Mean (RTM) Bias (adapted from AASHTO 2010).

2.3 Methods of Safety Analysis

As described in Section 2.1, highway safety analysis methods are evolving from being descriptive to being quantitative and predictive in nature. Traditional descriptive analysis focuses on summarizing and analyzing historical crash data. Newer safety studies often use predictive analysis methods, such as Bayesian statistical models, to find and compare the expected average crash frequency at a site under varying conditions. This section discusses the methods associated with traditional descriptive analysis and those associated with predictive analysis.

2.3.1 Traditional Descriptive Analysis

Methods such as crash frequency, crash rate, and equivalent property damage only (EPDO) are typically used in traditional highway safety studies. As described in Section 2.2.1, a crash frequency is the number of crashes that occur in a specific period of time. A crash rate incorporates a measure of exposure and can be interpreted as the probability of a crash occurring for one unit of exposure. Equation 2-2 show how a crash rate is calculated (AASHTO 2010).

$$\text{Crash Rate} = \frac{\text{Average Crash Frequency in a Period}}{\text{Exposure in Same Period}} \quad (2-2)$$

The EPDO method involves assigning weighting factors to crashes by crash severity in order to develop a combined frequency and severity score. Weighting factors are assigned based on the cost of a crash relative to property damage only (PDO) crash costs.

Crash frequency and crash rates can be useful in studies to identify and prioritize sites that are in need of safety improvement. They can also be used in safety effectiveness evaluation. Crash frequency and crash rates are relatively simple to obtain and readily understood by the public. However, care should be taken in the use of crash frequency and crash rates. When used alone, neither method takes into account RTM and may result in ineffective investment of safety improvement funds (AASHTO 2010). Additionally, crash rates assume that a linear relationship exists between crashes and exposure. Even if a relationship between crashes and exposure exists, recent studies indicate that this relationship is not linear (Hauer et al. 2002; Qin et al. 2004).

2.3.2 *Predictive Analysis*

Predictive highway safety analysis makes use of advanced statistical models to address RTM and provide reliable estimates of expected average crash frequencies. These models use regression analysis to predict the number of crashes that can be expected to occur under a given set of conditions, including both existing and future conditions. These statistical models generally incorporate both historic crash data as well as crash data from a range of similar sites. The following subsections discuss the role that crash prediction models, crash modification factors (CMFs), crash reduction factors (CRFs), and statistical methods play in the predictive analysis process.

2.3.2.1 Crash Prediction Models

The type of crash prediction model used in the HSM is a safety performance function (SPF). An SPF uses regression equations to quantitatively estimate the average crash frequency for a specific site type (with specified base conditions) as a function of roadway characteristics such as annual average daily traffic (AADT) and segment length (AASHTO 2010). The base conditions for an SPF may include a number of roadway geometric characteristics including lane width, the presence of turn lanes, etc. An SPF provides a predicted average crash frequency of a roadway segment based on the crash behavior of similar sites. If the conditions of a roadway differ from the base conditions of an SPF, CMFs can be applied to adjust the predicted estimate of crash frequency.

Although SPFs are used extensively in the HSM predictive method, the Volume 1 (Schultz et al. 2010) and Volume 2 (Saito et al. 2011) reports have developed alternate crash prediction models that can be used to generate predictions of roadway safety. Crash predictions play a key role in network screening and evaluation processes. The Volume 2 report discusses the development, characteristics, and applications of crash prediction models in more detail.

2.3.2.2 Crash Modification Factor (CMFs) and Crash Reduction Factors (CRFs)

A CMF is “the ratio of the effectiveness of one condition in comparison to another condition” (AASHTO 2010, p. 3-19) and can be represented with Equation 2-3, where, in general, condition ‘a’ is the ‘before’ condition and condition ‘b’ is the ‘after’ condition.

$$CMF = \frac{\text{Expected Average Crash Frequency with Site Condition 'b'}}{\text{Expected Average Crash Frequency with Site Condition 'a'}} \quad (2-3)$$

A CMF of less than 1.0 indicates that the safety of a site improves with a change to condition 'b' whereas a CMF of greater than 1.0 indicates that the safety decreases. CMFs can be used to estimate the expected change in crash frequency due to a change in a particular feature of the roadway (AASHTO 2010). Alternative actions and countermeasures can be compared and evaluated based on CMFs. As mentioned in Section 2.3.2.1, CMFs can also be used to adjust an SPF predicted average crash frequency if roadway conditions vary from the base conditions of the SPF. CMFs are developed through effectiveness evaluation studies, which are discussed in more detail in Section 3.6.2 of this report.

A related measure of the effectiveness of a crash countermeasure is a CRF, which represents a percentage crash reduction that might be expected after countermeasure implementation. A CRF and a CMF are related according to Equation 2-4 (AASHTO 2010). For example, a CMF of 0.8 would equate to a CRF of 0.2, or a 20 percent reduction in expected crashes.

$$CRF = (1 - CMF) \quad (2-4)$$

2.3.2.3 Statistical Methods

Predictive crash analysis uses Bayesian statistical methods, which base statistical inference on prior knowledge and the likelihood of the occurrence of certain types of events. Incorporation of these elements into Bayes theorem translates probabilistic statements into degrees of belief that a given event will occur (AASHTO 2010).

Recently, much attention has been given to the use of the Empirical Bayes (EB) method to combine observed crash data with predictive safety estimates to obtain an estimate of the expected crash frequency at a site. The EB method satisfactorily accounts for the effects of RTM even if only a few years of crash data are available (Hauer 1997). Although it is more complex than most methods of traditional analysis, the EB method can readily be applied. Therefore, the HSM recommends the use of the EB method and extensively uses this method in its predictive method (AASHTO 2010).

Another statistical approach to crash analysis is the hierarchical or full Bayes method, which also accounts for RTM in safety analysis. Although the hierarchical Bayes method requires greater expertise in statistical methods, it has many attractive characteristics (Gross et al. 2010). Using the hierarchical Bayes method, complex model forms can be developed which enhance the utility of the model by being able to include both multiplicative and additive terms. Another benefit of the hierarchical Bayes method is that valid models can be estimated with smaller sample sizes. Use of this statistical method allows for the consideration of spatial correlation between crash sites. Finally, the hierarchical Bayes method affords a more flexible approach of integrating prior knowledge into analysis models (Olsen et al. 2011). Prior knowledge in the EB method is based solely on the set of crash data being analyzed while the hierarchical Bayes method can make use of a more informative prior distribution that incorporates findings of observational studies and expert opinion.

2.4 HSM Roadway Safety Management Process

Part B of the HSM outlines a Roadway Safety Management Process that highway agencies can use to monitor, improve, and maintain the safety on the existing roadway networks (AASHTO 2010). The process moves in a logical order, describing first how to identify sites in need of safety mitigation, second how to effectively select economically valid countermeasures for those sites, and last how to evaluate the effectiveness of implemented projects. The components of the HSM Roadway Safety Management Process are outlined and discussed in Chapter 3 of this report. The Roadway Safety Management Process in the HSM closely follows and supports the process for highway safety improvement found in the HSIP Manual (Herbel et al. 2010). Thus, utilizing the HSM Roadway Safety Management Process can aid UDOT in meeting the HSIP objectives for the state.

2.5 Chapter Summary

In summary, transportation policy mandates that state transportation officials increasingly integrate safety into roadway planning, design, operations, and maintenance. In order for optimal decisions on highway safety investment to be realized, effective analytical tools and methods are needed. The HSM as well as other ongoing research efforts are helping safety analysis to evolve

into a more quantitative, science-based process that can be used to predict changes in safety under different conditions. Understanding terms, concepts, and methods that are fundamental to safety analysis will aid state transportation officials in applying safety mitigation measures. The framework for safety mitigation in Chapter 3 outlines the process by which UDOT can use crash analysis methods to identify safety ‘hot spots,’ implement cost-effective treatments, and improve future decision-making and policy.

THIS PAGE INTENTIONALLY LEFT BLANK

3 FRAMEWORK FOR HIGHWAY SAFETY MITIGATION

Many components are involved in highway safety improvement. For this report, the HSM Roadway Safety Management Process is used as a basis for developing a framework for highway safety mitigation. The contents of this chapter are intended primarily as an overview of the core ideas of each component of the safety mitigation process. A more comprehensive discussion of these components with specific methods and examples is provided in the HSM (AASHTO 2010). Analysis methods developed in the Volume 1 (Schultz et al. 2010) and Volume 2 (Saito et al. 2011) reports will also be discussed in the appropriate step of the process, providing a context for their application. The following framework for highway safety mitigation includes: network screening; diagnosis; countermeasure selection; economic appraisal; project prioritization; and safety effectiveness evaluation. The purpose of each part of this mitigation framework is summarized in Figure 3-1.

3.1 Network Screening

Network screening is a process for reviewing a transportation network to identify safety ‘hot spots,’ or sites that can benefit most from safety improvement (AASHTO 2010). This process involves examining and comparing the crash behavior of many sites to identify those that have a higher proportion of crashes than would be expected. The network screening process plays a crucial role in fulfilling the mandate set forth by the HSIP to improve highway safety (Herbel et al. 2010). Sites that are identified as having an unusually high crash frequency can be further examined and improved where appropriate. Sites found to have the highest need for safety improvement can be included in UDOT’s annual *5 Percent Report* (UDOT 2011a).

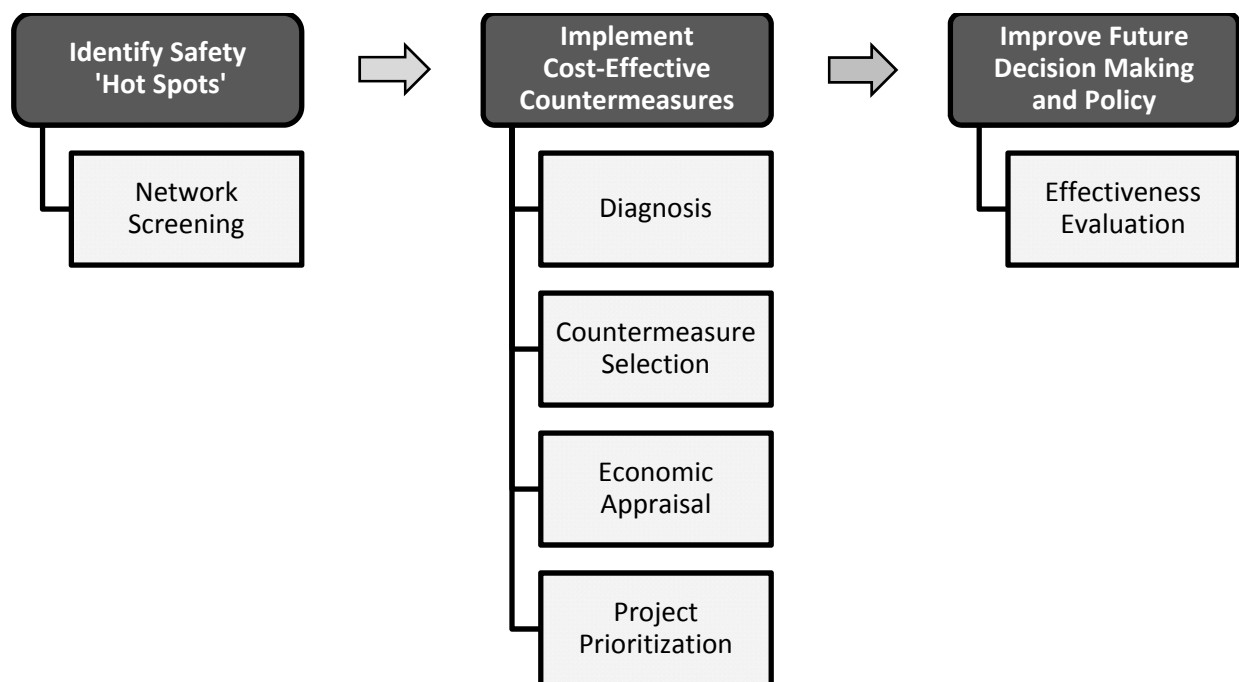


Figure 3-1. Framework for highway safety mitigation.

The HSM divides the network screening process into five major steps: 1) establish focus; 2) identify network and establish reference populations; 3) select performance measures; 4) select screening method; and 5) screen and evaluate results (AASHTO 2010). Each step is briefly discussed in the following sections, while the *HSM* and the *HSIP Manual* contain a more detailed explanation of each step (AASHTO 2010, Herbel et al. 2010). This section concludes by discussing the application of jurisdiction-specific crash prediction models developed in the Volume 2 report (Saito et al. 2011).

3.1.1 Establish Focus

The first step in the network screening process is to determine the reasons for screening and establish the focus of the analysis. The screening process can be undertaken either to identify potential sites that could benefit most from safety improvement or to develop a system wide policy for reducing a target crash type or crash severity (AASHTO 2010). Considerations in this step involve determining analysis area, target crash types and severities, and the overall purpose of conducting the analysis. For example, a highway agency wants to determine where cable barrier should be installed on divided two-lane highways. They need to first determine which

two-lane highways should be included and then determine which types of crashes can be reduced by the installation of cable barrier. In this case, fatal and severe injury crashes might be selected as the target crash type. The purpose of the analysis would then be to determine which sites along the selected two-lane highways that could have the largest reduction in fatal and severe injury crashes.

3.1.2 Identify the Network and Establish Reference Populations

This second step of the network screening process involves identifying network elements to be screened and organizing them into groups, known as reference populations. Reference population groups should contain specific sites included that have similar characteristics. Organizing sites into reference populations allows the crash frequency of individual sites to be compared to the expected crash frequency derived from all sites within the reference population (Herbel et al. 2010). Sites with relatively high crash frequencies can then be examined closer.

Reference populations of intersections could be established based on traffic control, number of approaches, approach cross-sections, functional classification, area type, traffic volume, and terrain. Reference populations for roadway segments could be established on the number of lanes per direction, access density, traffic volume, median characteristics, speed characteristics, adjacent land use, terrain, and functional classification.

3.1.3 Select Performance Measures

The third step of the network screening process is determining performance measures by which the safety of sites will be evaluated. Safety performance can be quantitatively measured in a similar manner that traffic operational performance can be measured by criteria such as vehicle delay, queue length, or volume-to-capacity ratio. The HSM presents a wide selection of possible safety performance measures and lists the strengths and limitations of each (AASHTO 2010). Consideration should be taken of complexity, data needs, and stability when selecting performance measures. Stability is the ability of a performance measure to reliably describe the safety performance of a site. Performance measures that account for RTM bias and provide performance thresholds are considered more stable. A performance threshold is a critical value that provides a reference point for the comparison of performance scores within a reference

population. Sites with scores above the threshold should be studied in more detail to determine if a reduction in crash frequency or severity is possible. Summary tables of the data needs and stability of possible performance measures are shown in Tables 3-1 and 3-2 respectively.

3.1.4 Select Screening Method

The fourth step of the network screening process is selecting the network screening method. The HSM presents three screening methods: 1) sliding window method; 2) peak searching method; and 3) simple ranking method (AASHTO 2010). The screening method should be chosen based on network elements in the analysis and the performance measure selected from Tables 3-1 and 3-2. For network screening, highway facilities can be broken into two elements - segments and nodes. A segment is a portion of a facility defined by two end points. A node is a point or area of a facility (e.g., intersection). Facilities are portions of the network that contain both segments and nodes. The recommended screening methods for each network element type are shown in Table 3-3 and discussed further in subsequent subsections. Each screening method is used in applying performance measures to determine sites with the greatest potential for crash frequency reduction.

3.1.4.1 Sliding Window Method

The sliding window method can only be applied to segments. It uses a window of a specified length that is conceptually moved incrementally from the beginning to the end of a roadway segment. The chosen performance measures are applied to each position of the window. The window position showing the most potential for reduction in crash frequency is identified and used to represent the potential for crash frequency reduction on the whole segment. After this method is applied to all of the segments in the reference population, segments can be ranked according to their potential for crash frequency reduction (AASHTO 2010).

Table 3-1. Summary of Data Needs of Performance Measures (AASHTO 2010)

Performance Measures	Data and Inputs				
	Crash Data	Roadway Information for Categorization	Traffic Volume	Calibrated SPF and Overdispersion Parameter	Other
Average Crash Frequency	X	X			EPDO Weighting Factors Relative Severity Indices
Crash Rate	X	X	X		
EPDO Average Crash Frequency	X	X			
Relative Severity Index	X	X			
Critical Rate	X	X	X		
Excess Predicted Average Crash Frequency Using Method of Moments	X	X	X		
Level of Service of Safety	X	X	X	X	
Excess Predicted Average Crash Frequency Using SPFs	X	X	X	X	
Probability of Specific Crash Types Exceeding Threshold Proportion	X	X			
Excess Proportion of Specific Crash Types	X	X			
Expected Average Crash Frequency with EB Adjustment	X	X	X	X	
EPDO Average Crash Frequency with EB Adjustment	X	X	X	X	EPDO Weighting Factors
Excess Expected Average Crash Frequency with EB Adjustment	X	X	X	X	

Table 3-2. Stability of Performance Measures (AASHTO 2010)

Performance Measure	Accounts for RTM Bias	Roadway Information for Categorization
Average Crash Frequency	No	No
Crash Rate	No	No
EPDO Average Crash Frequency	No	No
Relative Severity Index	No	Yes
Critical Rate	Only considers data variance	Yes
Excess Predicted Average Crash Frequency Using Method of Moments	Only considers data variance	Yes
Level of Service of Safety	Only considers data variance	Expected average crash frequency $\pm 1.5\sigma$
Excess Predicted Average Crash Frequency Using SPFs	No	Predicted average crash frequency at the site
Probability of Specific Crash Types Exceeding Threshold Proportion	Not effected by RTM bias	Yes
Excess Proportion of Specific Crash Types	Not effected by RTM bias	Yes
Expected Average Crash Frequency with EB Adjustment	Yes	Expected average crash frequency at the site
EPDO Average Crash Frequency with EB Adjustment	Yes	Expected average crash frequency at the site
Excess Expected Average Crash Frequency with EB Adjustment	Yes	Expected average crash frequency per year at the site

Table 3-3. Recommended Screening Methods for Network Elements

Network Element	Screening Methods
Segments	Sliding Window Peak Searching Simple Ranking
Nodes	Simple Ranking Variation of Peak Searching
Facilities	Simple Ranking

3.1.4.2 Peak Searching Method

The peak searching method is primarily applicable to segments, though the HSM suggests that a variation of this method can be used for nodes (AASHTO 2010). In this method, an individual segment is subdivided into windows of similar length. The chosen performance measures are applied to each window and the statistical precision of each performance measure calculation is observed. If the desired statistical precision is met for any of the windows, the maximum value in those windows is set as the performance of the segment. If the desired precision is not met by any of the windows, the length of the windows is expanded and the procedure is repeated. The windows should not overlap. This process is repeated until a window exceeds the desired precision or until the window is equal in length to the segment. After a measure of performance for each segment has been obtained, the segments are ranked according to their potential for crash frequency reduction (AASHTO 2010).

3.1.4.3 Simple Ranking Method

The simple ranking method can be applied to nodes, segments, or facilities. This method involves applying chosen performance measures to all sites under consideration and then ranking the results from high to low. There is no need to divide segments into windows in this method. For facilities, roadway segments of 5 to 10 miles are recommended for more stable results (AASHTO 2010).

In the analysis of roadway segments, it is advantageous to use the sliding window or peak searching methods as it is useful to determine the exact location within the roadway segment that will most benefit from safety improvement. Further investigation of this specific location will make the selection of effective countermeasures easier and more efficient. The simple ranking method can also be used on segments but produces less reliable results.

As stated in Section 3.1.4, screening methods should be chosen based on both network elements and on the chosen performance measures. The reader is encouraged to consult the HSM for further detail on which screening methods are appropriate for each type of performance measure (AASHTO 2010, pp. 4-19).

3.1.5 Screen and Evaluate Results

The fifth and final step to the network screening process is to apply the performance measures and screening methods discussed in Steps 3 and 4 and evaluate the results. The product of the network screening analysis is a list of sites ranked according to potential for safety improvement. These results can either be recorded in a table or on maps as desired. Repeating the network screening process using multiple performance measures on the same data set can be beneficial in identifying which sites will most benefit from safety improvement (AASHTO 2010). Sites with the highest potential for crash reduction can be studied in more detail to find suitable countermeasures.

3.1.6 Application of Jurisdiction-Specific Crash Prediction Models (from Volume 2 report)

The predicted crash frequency for a site can be obtained using crash prediction models. A comparison of the predicted crash frequency with the observed crash frequency can be useful in identifying safety ‘hot spots.’ Findings of the Volume 2 report show that the HSM SPF predictive method needs to be adjusted by a calibration factor of 1.16 for Utah rural two-lane two-way highways, which indicates that the HSM predictive method under predicts the number of crashes that occur on these highways (Saito et al. 2011). In an effort to better predict crashes, five new jurisdiction-specific models were developed for rural two-lane two-way highways in Utah. Four of these are negative binomial models; the other is a hierarchal Bayesian model, which is mathematically more complex but has the ability to more reliably predict crashes.

The models developed in the Volume 2 report can be used in the network screening process to identify ‘hot spot’ segments of roadway. In the negative binomial models, the observed crash frequency can be compared to the predicted crash frequency. If the observed crash frequency is substantially higher than the predicted crash frequency at a given site, closer examination of the site should be considered.

A distribution of the predicted crash frequency rather than just a point estimate can be found by using the hierarchal Bayesian model. The resulting distribution can be compared to the observed crash frequency to determine if the site is experiencing an unusually high number of crashes. Figure 3-2 shows how safety ‘hot spots’ can be identified through the use of a hierarchal Bayesian model. Since the observed crash frequency is outside of the distribution of predicted

crashes, this particular site can be said to experience an unusually high crash frequency (Saito et al. 2011).

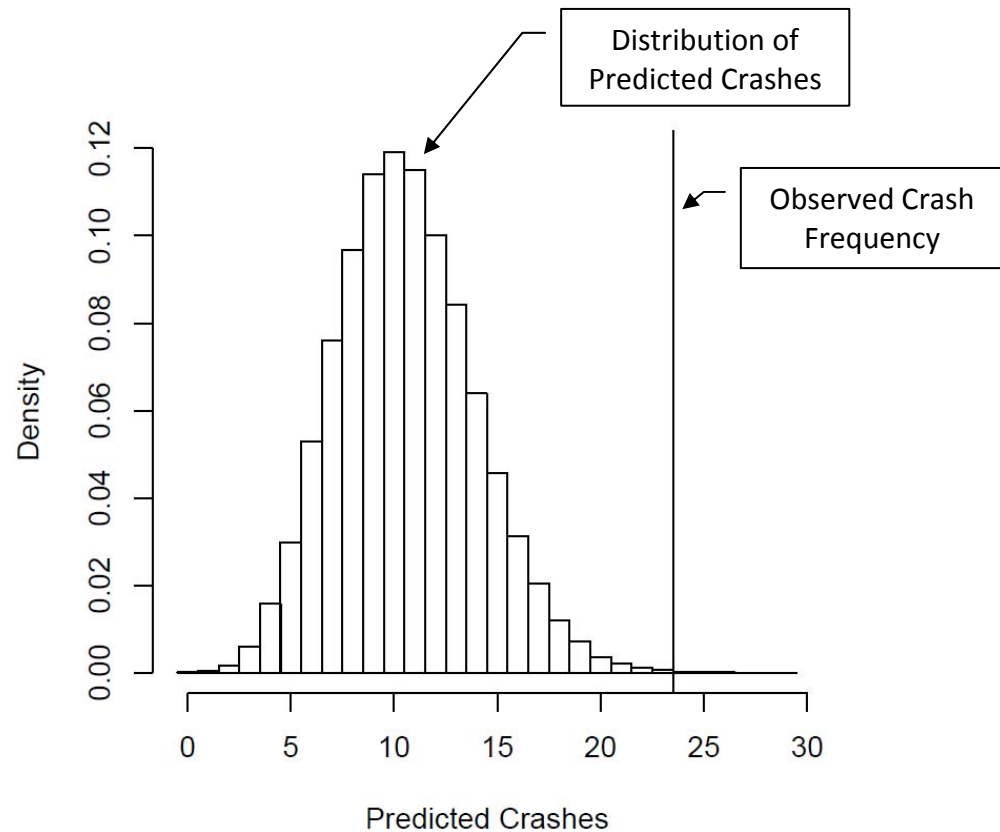


Figure 3-2. ‘Hot spot’ analysis using a hierarchal Bayesian model (adapted from Saito et al. 2011).

For many applications, the simpler negative binomial models may provide reasonable crash prediction results. However, the hierarchal Bayesian model more accurately predicts crash frequency and better accounts for variability in crash data. Although the particular jurisdiction-specific models developed in the Volume 2 report are for rural two-lane two-way roads, the same prediction models could be developed for other roadway types in the state. These jurisdiction-specific crash prediction models can enhance the ability of UDOT to effectively identify sites with unusually high crash frequencies.

3.2 Diagnosis

Diagnosis is the first step in implementing cost-effective countermeasures to mitigate crash frequencies. This process involves closely examining sites identified as ‘hot spots’ in the network screening process to understand crash patterns. The objectives of diagnosis are to identify factors contributing to crashes and other safety concerns at these locations.

The HSM outlines three sources of data that should generally be examined in the diagnosis process (AASHTO 2010). Not all sources of data need to be reviewed in every project. The data sources are: 1) safety data; 2) supporting documentation; and 3) field conditions. Each of these data sources are discussed in the following subsections.

3.2.1 *Safety Data*

Reviewing existing safety data may lead to a better understanding of crash patterns and the identification of contributing crash factors. Safety data includes information about crashes that have occurred at the site of interest. This data may contain both descriptive statistics of crash conditions and recorded details about the crash location.

Descriptive statistics of crash conditions include such information as the time the crash occurred, crash type, crash severity, sequence of events, and contributing circumstances (AASHTO 2010). This information is compiled from police reports and provides useful information about the possible human, vehicle, and roadway factors contributing to the crash. Available crash data for a site should be analyzed to determine if there are trends in crash type, crash severity, or roadway environmental conditions such as pavement, weather, or lighting conditions. Additionally, attributes of involved drivers and the sequence of events leading to the collision should be examined for patterns. Graphical summaries of crash data including bar charts, pie charts, and tabular summaries make patterns more visible and easier to identify. An example graphical summary of intersection crashes is presented in Figure 3-3.

A greater understanding of the cause of crashes can also come from characteristics of the crash location. Three tools are commonly used to summarize crash location characteristics – collision diagrams; condition diagrams; and crash mapping (AASHTO 2010). A collision diagram is a two-dimensional plan view of the site that shows a simplified representation of the crashes that have occurred. Collision diagrams can be helpful in visualizing crash patterns and

can be created by hand or using computer software. A sample collision diagram is shown in Figure 3-4. A condition diagram facilitates the identification of physical roadway and environmental characteristics that contribute to the occurrence of crashes. A condition diagram is a plan view of a site that should include features of the roadway, adjacent land uses, and pavement conditions. The condition diagram, in conjunction with the collision diagram, can be used to identify site characteristics that may be contributing to crashes. A sample condition diagram is shown in Figure 3-5.

Crash mapping may also be useful in the analysis of a crash location. It integrates electronic crash databases into a Geographic Information Systems (GIS) database to make spatial crash trends more visible (AASHTO 2010). Advantages of crash mapping include the ability for multiple data sets and documents to be integrated into a single tool for crash analysis, allowing for easier and more advanced crash analysis. However, crash mapping requires geocoded crash data and more technical expertise than simpler crash location tools.

3.2.2 Supporting Documentation

In addition to reviewing safety data from a crash database, other sources of information that create a deepened understanding of safety issues should be reviewed in the second step of the diagnosis procedure. This information helps build an understanding of the historical and operational context of the site, allowing additional factors contributing to crashes to be identified (AASHTO 2010). Information such as traffic volumes, as-built construction plans, design criteria, maintenance logs, land use maps, transportation studies, and records of public comments about the site should be reviewed. Additionally, the testimony of local transportation professionals about the characteristics of the site of interest should be obtained and assessed.

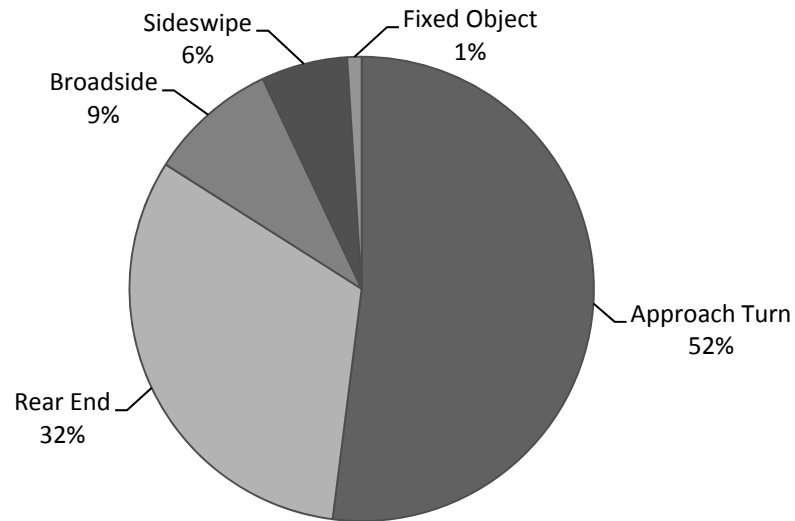


Figure 3-3. Example graphical summary of intersection crashes (adapted from Herbel 2010, p. 3-2)

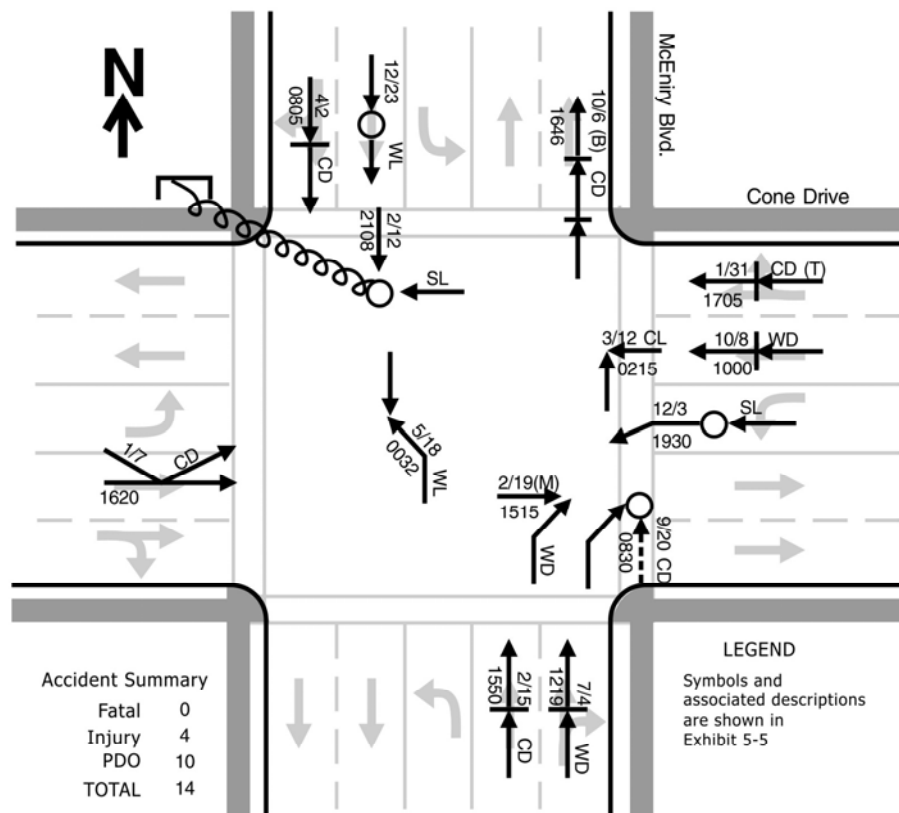


Figure 3-4. Example collision diagram (AASHTO 2010).

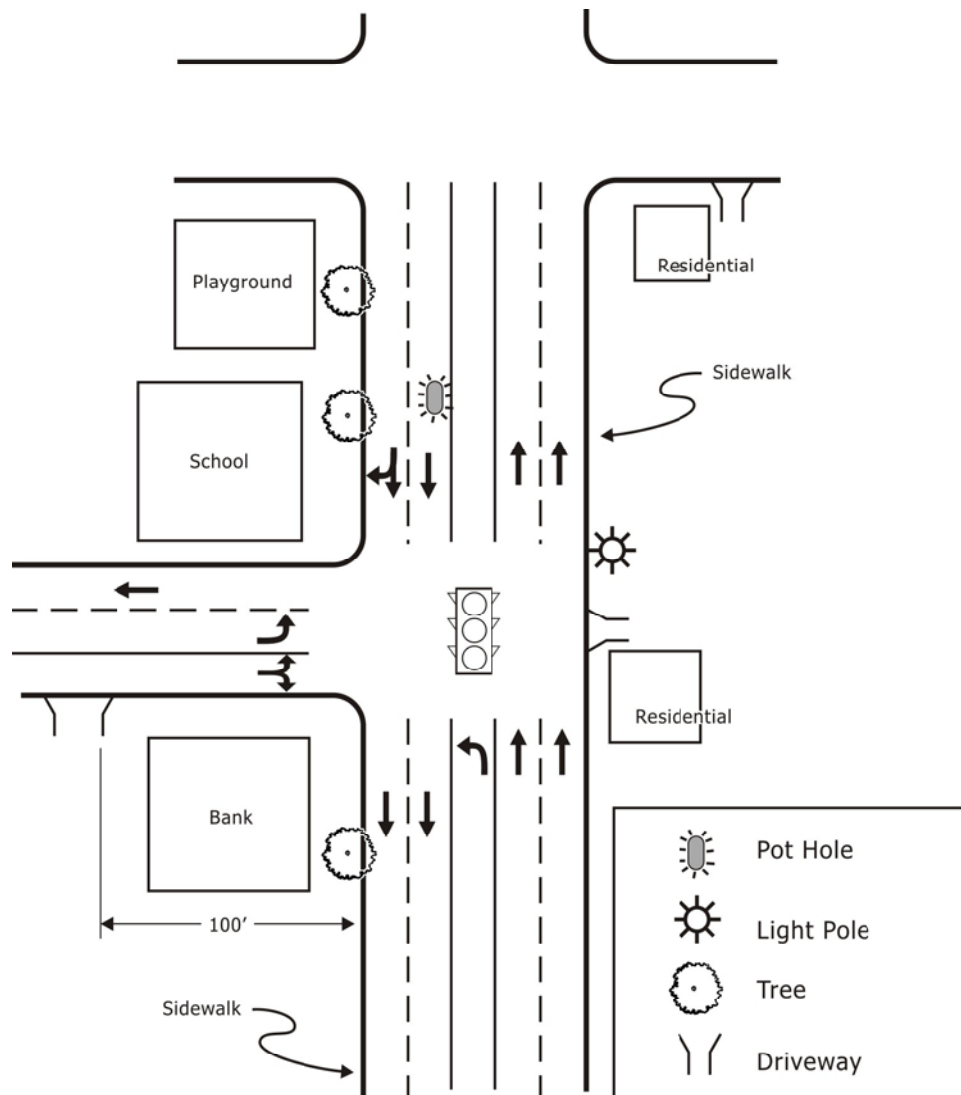


Figure 3-5. Example condition diagram (AASHTO 2010).

3.2.3 Field Conditions

A well-planned visit to the field can provide valuable first-hand knowledge about the characteristics of the site not apparent in recorded descriptions. Insights provided through a field investigation can help validate crash theories generated while reviewing safety data and supporting documentation (AASHTO 2010). During a field investigation, the observer should strive to notice and record the “typical” experience of a person traveling to and through the site. Observations of the site should include the physical roadway and environment; traffic conditions; and behavior of drivers, bicyclists, and pedestrians. Furthermore, evidence of problems such as broken glass, skid marks, and damaged objects near the roadway should be noted. Consideration

should also be given to the effect of different times of day and adverse weather conditions. A field review checklist can facilitate a comprehensive assessment of site characteristics and conditions. The HSM provides a sample checklist for evaluation of field conditions (AASHTO 2010, p. 5-27).

3.3 Countermeasure Selection

After factors contributing to crashes have been identified, countermeasures that address these factors should be identified and appraised for cost effectiveness. Within the safety mitigation process, the words ‘countermeasure’ and ‘treatment’ are synonymous and refer to a roadway strategy intended to decrease crash frequency or severity at a site (AASHTO 2010).

Just as human, vehicle, and roadway factors may contribute to a crash, countermeasures can be developed and applied to mitigate each of these types of factors (AASHTO 2010). Educational programs, targeted enforcement, and graduated driver licensing can mitigate human factors contributing to crashes. Occupant restraint systems and in-vehicle technologies can mitigate vehicle factors contributing to crashes. Reports describing possible human and vehicle countermeasures have been published by the National Cooperative Highway Research Program (NCHRP) and by the National Highway Traffic Safety Administration (NHTSA) (NCHRP 1998, NHTSA 2010). These countermeasures are an important part of the overall safety mitigation process and can have a significant impact on reducing crash frequency and severity on roadways in Utah; however, the roadway safety management process focuses on ways to improve the safety performance of the physical roadway facilities through the use of roadway countermeasures.

There are three main steps in selecting a countermeasure for a site: 1) identify factors contributing to crashes; 2) identify potential countermeasures; and 3) select preferred treatment based on economic analysis. These steps are described in the following subsections.

3.3.1 Identify Factors Contributing to Crashes

The first step in the countermeasure selection process is the identification of possible factors contributing to a crash. Most of the information needed to identify these factors comes from the analysis of crash data and site characteristics discussed in Section 3.2. The crash

patterns identified during diagnosis may reveal many possible human, vehicle, and roadway factors that may contribute to a crash. The Haddon Matrix (AASHTO 2010; Haddon 1972) is a useful framework for logically organizing possible contributing factors into human, vehicle, and roadway categories; and into before, during, and after time periods of the crash. The Haddon Matrix facilitates identifying factors that create a hazardous situation, impact crash severity, and determine the outcome of the crash. Careful analysis of a Haddon Matrix can help identify crash factors that can be mitigated through engineering efforts. An example of a Haddon Matrix prepared for a rear-end crash is shown in Table 3-4.

The *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan* is a series of reports on possible countermeasures for numerous types of crashes (NCHRP 1998). This report series provides valuable tools to help transportation professionals identify appropriate countermeasures.

Table 3-4. Example Haddon Matrix for Rear-End Crash (AASHTO 2010; Haddon 1972)

Period	Human Factors	Vehicle Factors	Roadway Factors
<i>Before the Crash</i> (causes of hazardous situation)	distraction / inattention fatigue bad judgment age of passengers cell phone use impaired cognitive skills deficient driving habits	bald tires worn brakes	wet pavement polished aggregate steep downgrade poor signal coordination limited stopping sight distance lack of warning signs
<i>During the Crash</i> (causes of crash severity)	vulnerability to injury age of passengers failure to wear a seat belt	bumper heights and energy absorption headrest design airbag operations	pavement friction grade
<i>After the Crash</i> (factors of crash outcome)	age of passengers gender	ease of removal of injured passengers	the time and quality of the emergency response subsequent medical treatment

3.3.2 Identify Potential Countermeasures

The second step in the countermeasure selection process is identifying countermeasures to address the contributing factors identified in Step 1. Selecting potential countermeasures requires engineering judgment and local knowledge of the site (AASHTO 2010). A variety of countermeasures should be considered to address each contributing factor.

CMFs provide an indication of countermeasure effectiveness and can be useful in identifying potential countermeasures (AASHTO 2010). Countermeasures that have a CMF of less than 1.0 have the potential to reduce crashes at a site. Countermeasures can have the effect of reducing crash frequency, crash severity, or both. In some cases, a countermeasure might correlate with an increase in crash frequency but a reduction in crash severity. An example of such a countermeasure is cable barrier. Sites with cable barrier tend to have a higher number of overall crashes than comparable sites without them but the crashes tend to be less severe (Hunter et al. 2001; McInanahan et al. 2003; Schultz et al. 2010). Therefore, even though cable barrier has a CMF greater than 1.0 for overall crashes, they should not be discounted as a potential countermeasure for a site. Engineering judgment should be applied to make optimal decisions in selecting countermeasures. If a CMF for a particular countermeasure is not available, a CMF can be developed according to the methods discussed in Section 3.6.

The specific contributing factor or associated treatment may not always be easy to identify even when a site is known to have a safety concern. An evaluation of segments upstream or downstream of the site could reveal conditions that might influence the safety performance of the site. Also, further monitoring and study of the site could reveal potential contributing factors or solutions that were not evident before.

3.3.3 Select Preferred Treatment based on Economic Appraisal

The final step in the countermeasure selection process is selecting a preferred treatment based on an economic appraisal of the project (AASHTO 2010). The potential countermeasures identified in Step 2 can be compared based on the anticipated cost and effectiveness of the treatment. Cost-benefit analysis is a commonly used method for appraising the relative value of implementing countermeasures and is discussed in more detail in Section 3.4. The

countermeasure offering the most value should be selected as the preferred treatment and implemented as resources allow.

3.4 Economic Appraisal

Although many countermeasures have potential to improve safety at a given site, economic realities necessitate that in most cases only economically viable projects be considered for implementation. This step of the roadway safety management process involves comparing the benefits of a countermeasure to its project costs. An economic appraisal of potential countermeasures will provide a quantitative benefit-to-cost ratio (BCR) for selecting and prioritizing the implementation of treatments (AASHTO 2010).

For economic appraisal, the costs of a project are always measured in monetary terms. However, project benefits can be addressed in two different ways – benefit-cost analysis; and cost-effectiveness analysis (AASHTO 2010). Both ways quantify project benefits based on the estimated reduction of crash frequency or crash severity that results from the implementation of the treatment. In benefit-cost analysis, the estimated reduction in crash frequency or severity is converted into monetary values and compared to the monetary cost of implementing the countermeasure. For cost-effectiveness evaluation, the estimated reduction in crashes is compared directly to the monetary cost of the implementing the countermeasure. The economic appraisal process involves three primary steps: 1) assess expected project benefits; 2) estimate project costs; and 3) apply economic evaluation methods.

3.4.1 Assess Expected Project Benefits

The first step of economic appraisal is determining the expected safety benefits of a project. Only benefits associated with a change in crash frequency are considered in this appraisal (AASHTO 2010). Aside from a reduction in crash frequency, safety improvements can have other benefits. Some of these benefits are quantifiable such as reducing congestion that results from crashes, and improving both roadway operations and air quality. Other benefits are more qualitative in nature such as meeting established community-endorsed policies to meet road user needs, satisfy public demand, and provide a solution that is consistent with the vision of the

community. These benefits should be included in the overall decision making process but are not given economic value in this appraisal.

Project benefits are measured first in terms of a quantitative change in crash frequency or severity. Therefore, the first step to assessing project benefits is determining the expected average crash frequency under existing conditions and comparing it with the expected average crash frequency for conditions after the proposed countermeasure is implemented. Crash analysis methods that account for RTM are recommended for determining the expected average crash frequency for both existing and proposed conditions. The HSM recommends using the predictive method in Part C of the HSM in determining the expected change in crash frequency between existing and proposed conditions (AASHTO 2010).

SPFs alone may be used to estimate the expected crash frequency of the existing conditions but the estimate will not take into consideration the observed crash frequency of the site (AASHTO 2010). Locally derived crash prediction models may also be used in a similar manner. If the HSM predictive method is not used for the proposed conditions, the CMF of the proposed project should be used to estimate the expected crash frequency of the after period. Where no CMF exists for the proposed project, engineering judgment can be applied to estimate one.

After the expected change in crash frequency is obtained, the benefits of the project in monetary terms can be determined. The estimated change in crash frequency can readily be converted to a monetary value through the use of established societal crash costs (AASHTO 2010). Research completed by FHWA establishes a basis for converting into monetary terms the human capital crash costs of fatalities and injuries to society (AASHTO 2010; Council et al. 2005). These societal costs have been developed for crashes of each level of the KABCO scale. The costs included in the societal crash cost estimates include the monetary losses associated with medical care, emergency services, property damage, and lost productivity. They represent the cost of the crash to society as a whole. These values were recently updated to more accurately reflect the true cost of crashes (Duval and Gribbon 2008).

UDOT has established its own societal crash cost estimates (UDOT 2009). Crashes are categorized into five classifications based on crash severity and assigned a cost. The UDOT societal crash cost estimates use FHWA crash costs as base values but assign the same monetary value to both fatal and incapacitating injury crashes. This variation from FHWA reflects the

lifelong burdens and costs that an incapacitating injury incurs on society. Societal crash cost estimates established by FHWA and UDOT are shown side by side in Table 3-5.

An annual monetary value of the benefits of a project can be obtained by multiplying the expected change in crash frequency by the accepted societal crash cost for each crash severity and summing these costs together. This sum represents the annual monetary value of the benefits of the project. For example, if the reduction of one fatality, four incapacitating injury, and nine possible injury accidents in one year is attributed to a project, the benefits for that year would be just over 4.3 million dollars using UDOT societal crash costs.

The next step is to convert the annual monetary value of the benefits over the life of the project into present value so that it can be easily compared with costs of the project. The benefits can be converted into present value one of two ways, depending on if the annual benefits of the project are uniform or not over the life of the project. Both methods are explained in detail in the HSM (AASHTO 2010, pp. 7-6 and 7-7).

Table 3-5. UDOT and FHWA Societal Crash Costs by Severity (Duval and Gribbon 2008; UDOT 2009)

Severity Level	Collision Type	FHWA Cost / Crash	UDOT Cost / Crash
K	Fatal	\$5,800,000	\$785,000
A	Incapacitating injury	\$401,538	\$785,000
B	Non-incapacitating evident injury	\$80,308	\$80,000
C	Possible injury	\$42,385	\$42,000
O	Non-injury	\$4,462	\$4,400

3.4.2 Estimate Project Cost

The next step in economic appraisal is estimating the project cost. Estimating the cost of implementing a countermeasure is similar to determining cost estimates for any other construction or program implementation project (AASHTO 2010). Implementation costs are unique to each project but could include factors such as planning and design work, right-of-way acquisition, construction material costs, grading and earthwork, utility relocation, and environmental impact mitigation. Operation and maintenance costs over the service life of the

project should also be included. Converting all costs associated with project implementation to present value will allow the project cost to be easily compared with the present value of project benefits.

3.4.3 Apply Economic Evaluation Methods

The third and final step in conducting an economic evaluation on a countermeasure implementation project has two primary purposes (AASHTO 2010). The first is to determine if a project is economically justified. A project is economically justified if the benefits of the project exceed its implementation costs. The second purpose is to determine which project or alternative is most cost effective.

Evaluating if a project is economically justified can be done in two ways. The first is the net present value (NPV) method, which involves finding the difference between the present value of project benefits and project costs as shown in Equation 3-1 (AASHTO 2010). This method is also referred to as the net present worth (NPW) method. A project with a NPV greater than zero indicates that the project is economically justified.

$$NPV = PV_{benefits} - PV_{costs} \quad (3-1)$$

where: NPV = net present value,
 $PV_{benefits}$ = present value of project benefits, and
 PV_{costs} = present value of project cost.

The second method for determining if a project is economically justified is calculating a BCR, which compares the present-value benefits of a project to the implementation costs of the project. A project with a BCR greater than 1.0 is considered economically justified. Equation 3-2 shows how to calculate the BCR of a project (AASHTO 2010).

$$BCR = \frac{PV_{benefits}}{PV_{costs}} \quad (3-2)$$

An advantage of using the BCR method is that the magnitude of the BCR for an individual project indicates the relative desirability of implementing the project. However, the

BCR cannot be directly used to compare project alternatives or projects at multiple sites. An incremental benefit-cost analysis is needed for that type of comparison (AASHTO 2010). Even though the relative desirability of a project is not as easily understood using the NPV method as the BCR method, the NPV method allows projects and alternatives to be easily compared. The NPV method will rank projects in the same order as the incremental cost-benefit analysis, which is discussed in more detail in Section 3.5.1.

Determining which project or alternative is most cost-effective can be done using cost-effectiveness evaluation, which directly compares the predicted change in average crash frequency to project costs. This method is useful in gaining a quantifiable understanding of the value of implementing a countermeasure when converting a crash frequency reduction to a monetary value is not desired. Equation 3-3 can be used to calculate the cost-effectiveness of a safety improvement project (AASHTO 2010). This equation gives a cost-effectiveness index based on comparing the present value of project costs with the estimated change in average crash frequency over the life of the countermeasure. A lower cost-effectiveness index indicates that more crashes are prevented for the funds invested in a project.

$$\text{Cost – Effectiveness Index} = \frac{PV_{costs}}{N_{predicted} - N_{observed}} \quad (3-3)$$

where: $N_{predicted}$ = predicted crash frequency for the year, and
 $N_{observed}$ = observed crash frequency for the year.

The cost-effectiveness index gives a general sense of the value of an individual project, which can then be compared and ranked against other projects. However, this method does not indicate whether a project is economically justifiable as the benefits and costs of a project cannot be directly compared unless both are converted to a monetary value. Also, this method does not differentiate between different crash severities and thus may not give the best estimate of the value of a project (AASHTO 2010). For example, this method would place greater value on reducing four possible injury crashes than three fatalities for countermeasures having the same project costs.

3.5 Project Prioritization

The fifth step in the roadway management process is prioritizing safety improvement projects that have been deemed economically justifiable. Prioritization refers to “a review of possible projects or project alternatives and developing an ordered list of recommended projects based on the results of ranking and optimization processes” (AASHTO 2010, p. 8-2). The purpose of prioritization is to allocate safety improvement resources in such a way as to maximize the benefits for a given investment. It is based on the idea that safety improvements having the greatest benefit and lowest cost should be implemented first. Projects with lower benefits and/or higher cost can be implemented after to further enhance safety if desired. This section includes a brief discussion of: 1) ranking procedures; 2) optimization methods; and 3) multi-objective allocation.

3.5.1 Ranking Procedures

A simple method of prioritizing safety improvement projects is ranking, which is organizing projects according to a certain measure or index. Projects can be ranked from high to low based on economic effectiveness measures including project costs, monetary value of project benefits, reduction of crashes, cost-effectiveness index, and NPV. If ranking projects by BCR, an incremental benefit-cost analysis, described in the following paragraph, should be conducted. Ranking can be used to make simple improvement decisions but is insufficient if there are multiple competing objectives such as reducing crashes while still fitting a budget constraint (AASHTO 2010).

An incremental benefit-cost analysis is an iterative procedure that involves pairing economically justified projects and comparing their benefits and costs to determine the incremental BCR. Economically justified projects should be ordered by project cost. The incremental BCR can be found using Equation 3-4 (AASHTO 2010).

$$\text{Incremental BCR} = (PV_{benefits2} - PV_{benefits1}) / (PV_{costs2} - PV_{costs1}) \quad (3-4)$$

where: $PV_{benefits1}$ = present value of benefits for lower-cost project,
 $PV_{benefits2}$ = present value of benefits for higher-cost project,

$$PV_{costs1} = \text{present value of cost for lower-cost project, and}$$

$$PV_{costs2} = \text{present value of cost for higher-cost project.}$$

If the incremental BCR is a positive value greater than 1.0, the higher-cost project is preferred over the lower-cost project. Otherwise, the lower-cost project is preferred. The preferred project from the pair is then compared with the next project in the list. The preferred project from the final comparison is assigned the highest priority and removed from the list. This same process can be repeated to find the project with the second highest priority and so on until all projects are ranked in order of priority. The project with the highest priority is considered the best economic investment (AASHTO 2010). The use of spreadsheet or special purpose software is recommended to automate calculations and increase the efficiency and ease of this method.

3.5.2 Optimization Methods

Optimization is a process that identifies the most cost-effective set of improvement projects that fit within a fixed budget or other constraints. The HSM recommends three methods of optimization that can be used for the prioritization of safety projects (AASHTO 2010):

- Linear programming (LP) optimization
- Integer programming (IP) optimization
- Dynamic programming (DP) optimization

All three of these optimization methods use a mathematical technique to determine which combination of projects will provide the most benefit while still fitting within a constraint, such as a budget. More detail about each of these methods is provided in Chapter 8, Appendix A of the HSM (AASHTO 2010).

3.5.3 Multi-objective allocation

The methods of ranking and optimization discussed in Sections 3.5.1 and 3.5.2 are based solely on reducing crashes. However, other objectives often influence the selection and prioritization of highway improvement projects. Where there are multiple objectives being considered, a decision-making algorithm known as multi-objective resource allocation can be used. In this method, weights are assigned to each objective under consideration and an optimal

set of projects fitting these objectives can be found (AASHTO 2010). Two examples of multi-objective allocation methods that can be used in prioritizing highway projects are Interactive Multi-objective Resource Allocation (IMRA) (Chowdhury et al. 2000) and Multicriteria Cost-Benefit Analysis (MCCBA) (Roop and Mathur 1995).

3.6 Safety Effectiveness Evaluation

The last step of the roadway safety management process is safety effectiveness evaluation, which is intended to assess the change in safety brought about for implemented safety countermeasures. A safety effectiveness evaluation can be conducted to quantitatively estimate the effect that a treatment, project, or group of projects has on the expected average crash frequency or severity (AASHTO 2010). The results of such a study are an important part of assessing how well safety improvement funds have been invested. Furthermore, it can provide valuable information that can be used to improve future decision making and policy development.

The results of an effectiveness evaluation can be applied in numerous ways. First, the results can be used to evaluate the effectiveness of a treatment, whether it was implemented at only one site or at many sites. Second, it can be used to develop a CMF for a treatment based on the crash reduction associated with it. Such a CMF can then be used in the safety mitigation process at additional sites. Third, it can be used to assess the overall effectiveness of a treatment in comparison to its cost, giving a sense of how well safety improvement funding was utilized (AASHTO 2010).

This section will discuss: 1) types of effectiveness evaluation studies; 2) study designs; 3) a framework for safety effectiveness evaluation; 4) the development of CMFs; and 5) the economic appraisal of safety treatments. This section concludes with a discussion of the hierarchical Bayes approach to effectiveness evaluation developed in the Volume 1 report (Schultz et al. 2010).

3.6.1 Types of Effectiveness Evaluation Studies

An effectiveness evaluation can be conducted in either an experimental or an observational fashion (Gross et al. 2010). In an experimental study, inferences are made about

countermeasure effectiveness based on treatments implemented specifically for evaluation. Sites that have been identified for a treatment are randomly assigned to either a treatment or a control group. Treatments are implemented to sites in the treatment group after each site has been assigned to a group. In an observational study, inferences are made from data observations for treatments implemented due to normal efforts to improve the safety of the road system. In other words, treatments in an observational study are not implemented for the primary purpose of determining their effectiveness.

The controlled nature of an experimental study allows the difference in crash frequency between the treatment group and the control group to be directly attributed to the treatment (AASHTO 2010). However, due to ethical concerns of experimenting with the safety of highway users, most safety effectiveness evaluations are observational studies. In order to allow crash differences in observational studies to be more directly attributed to the treatment of interest, a set of similar, untreated sites can be used as a control group to account for changes in safety due to other factors.

3.6.2 Study Designs

There are two types of study designs can be used in safety effectiveness evaluation – before/after design; and cross-sectional design. The before/after design is generally preferred to the cross-sectional design.

In a before/after design, the safety of an entity is compared between the periods before and after the implementation of the treatment. Research by Gross et al. (2010) states that there are two primary considerations that need to be taken into account with a before-after study. The first is the sample size, which should be selected based on the magnitude of the treatment effect and on the uncertainty of the estimate. Generally, a larger sample size will have a lower level of uncertainty. The second is potential bias that may be present in the study due to factors such as changes in traffic volumes, changes in crash reporting. Factors such as these may affect the reported change in crash frequency between the before and after periods. RTM may also introduce bias into a study, as discussed in Section 2.2.5. Traditional before/after studies do not account for these biases and thus produce results that are considered unreliable or of poor quality.

In a cross-sectional design, the difference of safety between sites with and without a treatment of interest is compared. For example, the safety at yield controlled intersection approaches might be compared with that of stop controlled intersection approaches. The sites with the treatment should have similar characteristics to the sites without the treatment. Furthermore, the crash data used for analysis needs to be from the same time period. A rigorous before/after study design is preferred to the cross-sectional design. However, a cross-sectional design can be used when insufficient data exists to produce credible results using a before/after design (Gross et al. 2010).

3.6.3 Framework for Safety Effectiveness Evaluation

This section presents a framework for conducting a safety effectiveness evaluation developed from the general process followed in the Volume 1 report (Schultz et al. 2010). The five steps of this framework are: 1) determine focus and scope of study; 2) select the analysis model; 3) collect and reduce input data; 4) review outputs/results; 5) improve future decision making and policy development. Each of these steps will be described briefly in the following subsections.

3.6.3.1 Determine Focus and Scope of Study

The first step in an effectiveness evaluation of a given countermeasure is determining the scope and focus of the study. This involves selecting the type of study, the target crash types or crash severity, and identifying locations to be included in the study. As discussed in Section 3.6.2, an observational before/after study, an observational cross-section study, or an experimental before/after study can be used. A before/after study is preferred over a cross-sectional study (Gross et al. 2010). The target crash types or crash severities that will be analyzed should be selected based on the countermeasure. Some countermeasures are designed to reduce crash severity, not crash frequency. Finally sites where the countermeasure has been implemented should be identified. Sites should be selected in a random fashion, not based on a knowledge of the sites having a high crash frequency in the before analysis period (Hauer 1997).

3.6.3.2 Select Analysis Model

Selecting a safety analysis model is the second step in the process. Traditional descriptive analysis, which makes use of crash frequencies, crash rates, or EPDO estimates, can be used to evaluate changes in safety. Although such a study would be simpler, it would fail to take into account the effect of RTM and place restrictions on the amount of before and after data required (Hauer 1997). Therefore predictive analysis, which may use either the EB method or hierarchical Bayes method to obtain the expected average crash frequencies, is recommended.

3.6.3.3 Collect and Reduce Input Data

The third step in conducting an effectiveness evaluation is collecting relevant data and reducing it for analysis. This will usually include data about crashes, traffic volumes, and site boundaries. The data should be reduced in such a way that it can be input into the selected analysis model.

3.6.3.4 Review Outputs/Results

The fourth step is to review the results of the analysis and assess the change in safety experienced by sites included in the analysis. The results of the analysis should include a quantitative measure of safety along with an indication of the statistical significance of the change. The cause of unexpected results should be identified if possible. In addition to providing an indication of the effectiveness of a treatment, the analysis results can be used to develop CMFs and to appraise if safety funds were invested well.

3.6.3.5 Improve Future Decision Making and Policy Development

The last step in performing an effectiveness evaluation is considering how the findings of the study should be used in future decision making. CMFs developed in the study may be used in selecting potential countermeasures for future projects. Assessing the effectiveness and economic viability of a countermeasure can be used as a basis to make statewide policy changes. For example, based on effectiveness evaluation studies, the FHWA recommends implementing countermeasures such as rumble strip, cable barrier, and left- and right-turn lanes wherever possible (FHWA 2008).

3.6.4 *Development of Crash Modification Factors*

As discussed in Section 2.3.2.2, CMFs are a measure of how the crash experience at a site will change as a result of a safety treatment. For countermeasure applications, a CMF is a multiplicative factor that is used to compute the expected number of crashes after implementing a given countermeasure at a specific site (Gross et al. 2010). The change in crash frequency found in the results of an effectiveness evaluation can be used to develop CMFs. The HSM recommends that at least 10 to 20 sites be included in an effectiveness evaluation to obtain statistically significant results (AASHTO 2010). CMFs developed for a treatment of interest can be used in the decision making process as that treatment is again considered for implementation. A more detailed presentation of methodologies that can be used to develop CMFs can be found in *A Guide to Developing Quality Crash Modification Factors* (Gross et al. 2010).

3.6.5 *Economic Appraisal of Safety Treatments*

Highway agencies have limited funds for highway safety improvement and therefore strive to implement projects that maximize safety improvement for each dollar spent. Safety effectiveness evaluation can be used to assess how well safety improvement funds have been invested.

Conducting a cost-benefit analysis for treatments is a fairly simple process upon the completion of an effectiveness evaluation. This process follows the procedure outlined in Section 3.4. First, the benefits are calculated. The quantified change in safety from the evaluation represents the benefits, which can be converted to a monetary value through using societal crash costs. Second, the costs of implementing the treatment can be assessed. The actual construction costs can be combined with the expected maintenance costs for the design life of the treatment. Both the monetary value of the benefits and of the costs should be converted into present value. Finally, a BCR for the treatment can be found by comparing the benefits to the costs according to Equation 3-2 (AASHTO 2010). The BCR will give an indication of how well the treatment of interest provided a return on investment. An appraisal of an implemented treatment should also consider non-monetary effects of the treatment.

3.6.6 Hierarchal Bayes Effectiveness Evaluation (from Volume 1 report)

A new method was presented for conducting a safety effectiveness evaluation in the Volume 1 report. In this method, a hierarchal Bayesian model was developed as a tool that was used to compare the before and after expected average crash frequencies at selected locations (Olsen et al. 2011; Schultz et al. 2010; Schultz et al. 2011). Furthermore, this method was designed to account for the effects of RTM and to allow for flexibility in the modeling parameters.

The model was applied in an analysis of sites where raised medians and cable barrier systems had been installed. Six sites were included in the raised median analysis. Seven sites were included in the cable barrier analysis. Crash data, AADT data, and milepost data were included as data inputs in the analysis.

From the analysis on raised median sites, an estimate of the change in overall crashes and severe crashes at each site was found along with a probabilistic statement of if there was a crash reduction. From the analysis on cable barrier sites, an estimate of the change in overall crashes, severe crashes, and cross-median crashes was found along with a probabilistic statement of if there was a crash reduction. Figures 3-6 is an example of a graphical plot showing the decrease in severe crashes at raised median sites. Figure 3-7 is an example graphical representation of the probability that there was a decrease in severe crashes at raised median sites. Since the whole distribution is less than zero, there is a 100 percent probability that there was a decrease in severe crashes at raised median sites. More detail on the analysis procedure and results are available in the Volume 1 report (Schultz et al. 2010) and in the related TRB papers (Olsen et al. 2011; Schultz et al. 2011).

The raised median and cable barrier results of the Volume 1 report were intended to demonstrate the capabilities of the hierarchal analysis model developed as part of the research effort. No attempt was made to develop a CMF for either of the treatments included in the analysis. Furthermore, no economic analysis on the subject treatments was conducted. However, the results of the analysis could potentially be used in the development of CMFs and for an economic analysis of these treatments. The effectiveness evaluation method developed in the Volume 1 report can be applied in a similar manner to other roadway safety countermeasures in the future.

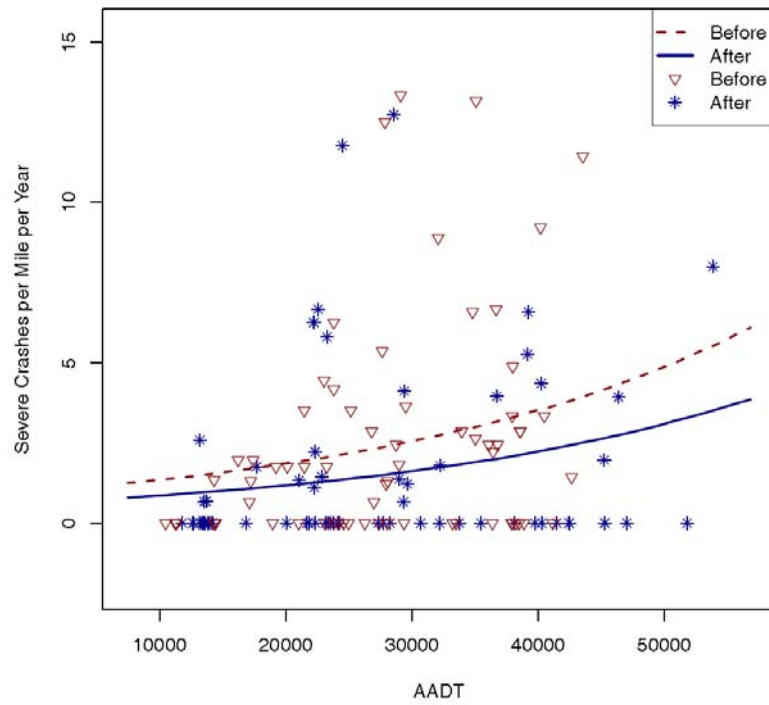


Figure 3-6. Severe crashes for all raised median study sites (Schultz et al. 2010).

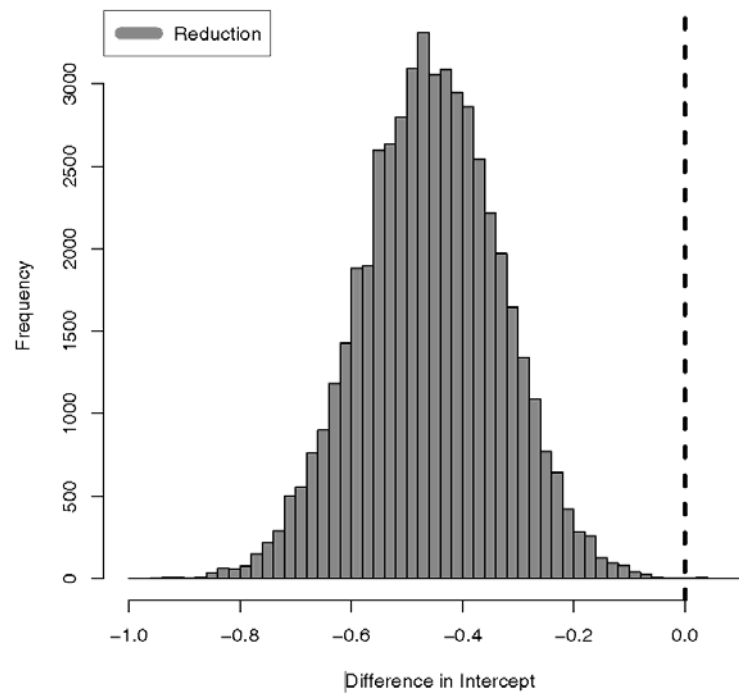


Figure 3-7. Distribution of differences of severe crashes for all raised median study sites (Schultz et al. 2010).

3.7 Chapter Summary

This chapter contains a framework for highway safety mitigation based on the HSM Roadway Safety Management Process. This process begins with identifying locations with high potential for safety improvement through network screening. Sites experiencing a higher number of actual crashes than what is predicted from the characteristics of a site (i.e., ‘hot spot’) should be further examined to determine how to best mitigate these crashes. Diagnosis of crashes is the first step in implementing cost-effective countermeasures. This process is aided by a combination of safety data, supporting documentation, and field visits that help build an understanding of existing safety concerns. Once potential contributing factors have been identified, appropriate countermeasures to reduce crash frequency, crash severity, or both can be identified and compared through economic appraisal. Priority in implementation should be given to projects that will maximize the safety benefits for every dollar spent. After a countermeasure has been implemented, a safety effectiveness evaluation can be conducted to determine the actual improvement of safety brought about by that countermeasure. Safety effectiveness evaluations can aid in future decision making and policy development.

The framework for highway safety mitigation outlined in this chapter can be a useful tool in aiding UDOT implement the HSIP and reduce target safety concerns in the state. However, transportation officials and professionals need to understand the concepts and tools involved in highway safety mitigation. Workforce training resources are available to help transportation officials and professionals integrate highway safety into decision making activities.

THIS PAGE INTENTIONALLY LEFT BLANK

4 SAFETY WORKFORCE DEVELOPMENT

Highway safety is a rapidly changing field. The consideration of safety in the design process has shifted from merely meeting design standards to comparing alternative designs based on the analysis of crash data to find the expected quantitative level of safety. Tools used in highway safety have evolved from using descriptive analysis of past crashes to those that predict an expected level of safety for a design, whether or not it has been built. Although advances in safety analysis tools have potential to substantially improve highway safety, transportation officials and professionals must first learn how to use these tools before this potential can be reached.

The purpose of this chapter is to present possible considerations involved with workforce development along with training resources that are currently available (as of March 2011). This chapter describes the current state of highway safety training resources; considerations of workforce development; and possible training opportunities related to highway safety. A summary of this chapter is also given.

4.1 Current State of Highway Safety Training Resources

Rapid strides are being made in the field of quantitative safety analysis; nevertheless, courses, workshops, and training on highway safety have only just begun to integrate state-of-the-art safety methods. The majority of on-the-job-training and practical workshops lag behind the advances in highway safety analysis and have not yet incorporated HSM methods into their curriculum. Furthermore, the highway safety training given to undergraduate and graduate college students is typically integrated into other courses and is limited in nature. As safety is playing a larger role in transportation planning and policy, highway safety training resources need to be updated to include recent advances in the field.

In an NCHRP funded effort to improve safety training resources, the TRB Task Force on Highway Safety Workforce Development (ANB23T) identified approximately 184 distinct courses and sessions that address highway safety (TRB 2010). These courses are in the process of being programmed into the AASHTO portal to multidisciplinary safety (AASHTO 2008). This portal is “is designed to be a clearinghouse of best practices, promising research efforts and the latest innovations in each discipline that are advancing traffic safety” (AASHTO 2008) and it represents a collaborative effort to improve highway safety. The portal is a forum facilitating the sharing of best practices and allows models, methods, and practices that work well in one organization to be more easily adopted by another. This resource will prove valuable to UDOT in their safety-related workforce development efforts.

4.2 Considerations of Workforce Development

Professionals in engineering, law enforcement, education and emergency response all play an important role in improving highway safety. Therefore, efforts to improve safety-related workforce development should consider more than just the needs of one particular group of professionals. The needs of those who would benefit from highway safety training should be identified and consider the knowledge, skills, and competencies that are needed to successfully integrate safety into the decisions they make. Up-to-date courses that will train professionals to the appropriate breadth and depth of knowledge needed in their individual tasks should be identified.

In addition to courses on highway safety, the TRB Task Force on Highway Safety Workforce Development (ANB23T) has identified the core competencies needed by various transportation professionals and is developing a comprehensive and integrated training roadmap to help professionals develop these competencies (TRB 2010). In developing this roadmap, the Task Force uses knowledge tables that are based on a learning framework developed from a working group of educators. This learning framework includes five forms of learning, which are shown in Table 4-1.

Table 4-1. Five Forms of Learning

Form of Learning	Description
Concepts	Learning based on definitions, diagrams, and models
Processes	Learning based on methodologies (i.e., information processing, design, teamwork, communication)
Tools	Learning surrounding forms/templates, software, and lab equipment
Contexts	Situations in which knowledge is applied
Ways of Being	Attitudes and values surrounding learning

Knowledge tables were developed for groups of practitioners having similar practicing requirements of safety competency. The groups were formed as follows:

1. Elected Officials
2. State DOT Management
3. Local Agency Management
4. State Mid-Level Management
5. Safety Engineers (Level 4)
6. Urban Planners (Level 2), Highway Designers, Safety Engineers (Level 3)
7. Urban Planners (Level 1), Traffic Engineers (Level 2), Field Investigators (RSA team members), Safety Engineers (Level 2)
8. Safety Data Collection and Management Specialists, Safety Analysis Specialists, Traffic Engineers (Level 1), Safety Engineers (Level 1), Field Investigators (crash reconstruction)
9. Safety Statisticians/Modelers, Safety Engineers (Level 5)

The knowledge tables created by the TRB Task Force show the concepts each group should understand and describes the processes and context where those concepts would be applied. Furthermore, the knowledge tables list potential tools and training resources that are available for each group. The information in these knowledge tables may be useful for UDOT in their safety workforce development program. The knowledge tables developed by the TRB Task

Force will be available in the final report from NCHRP project HR 20-7(290). This report has an anticipated completion date of May 31, 2011 (TRB 2011).

4.3 Possible Training Opportunities

Many courses are being developed that aim to help integrate safety into the transportation decision making process and bring state-of-the-art methods of safety analysis into practice. These courses include webinars, training sessions, workshops, and traditional classroom courses. A selection of possible training opportunities offered by: 1) FHWA, 2) the National Highway Institute (NHI), and 3) ITE are presented in this section. Additional resources that address highway safety training can be found online at the AASHTO portal to multidisciplinary safety (AASHTO 2008) and in the knowledge tables of the forthcoming NCHRP project HR 20-7(290) report.

4.3.1 FHWA Resource Center HSM Webinar Series

The FHWA Resource Center has created a webinar series to provide training on the HSM. Starting in June 2010, each session of this series has been recorded and posted on the official HSM website. Table 4-2 provides a list of these webinars with their corresponding lengths.

Table 4-2. HSM Webinars offered by FHWA Resource Center

Number	Webinar Title	Length
1	HSM Introduction and Overview	1 hr 25 min
2	Application to Two-Lane Rural Roads	1 hr 39 min
3	Application to Urban/Suburban Intersections	1 hr 08 min
4	Project Identification	1 hr 18 min
5	Application to Rural Two-Lane Intersections	1 hr 37 min
6	Application to Rural Multilane Highways	4 hr 05 min
7	Applications to Urban/Suburban Roads	1 hr 33 min
8	Applications to Rural Multilane Intersections	1 hr 39 min
9	HSM and Pedestrians	1 hr 23 min
10	Applications to Horizontal Curves	1 hr 14 min
11	HSM Relationship to Roadway Departure Crashes	1 hr 23 min
12	Applications to HSIP	1 hr 31 min

Note: Courses current as of March 2011

4.3.2 NHI Safety Training Courses

NHI, a division of FHWA, “works to improve the performance of the transportation industry through training” (NHI 2011). Among the training resources offered by NHI are numerous courses on highway safety that incorporate safety analysis methods from the HSM. These courses are separate courses from the FHWA HSM webinar series. The development of NHI highway safety courses is currently overseen by Thomas S. Elliot, an NHI Training Program Manager. Thirteen courses are shown in Table 4-3 that incorporate aspects of the HSM and represent a significant effort by the FHWA to encourage the integration of safety into the transportation decision-making process. The courses are current as of March 2011. The target audience of these courses is practitioners and decision makers at the state, county, metropolitan planning organization (MPO), or local level. The users and professionals described above include, but are not limited to transportation planners, highway designers, traffic engineers, and other transportation professionals who make discretionary road planning, design and operational decisions. Generally, NHI safety courses are designed for a class of between 20 to 30

participants. Many of these courses provide participants with additional course materials that will enhance the learning process.

Course 1 is intended to help participants identify opportunities for improving the manner in which safety is integrated into transportation decision making and programs. The course introduces participants to many fundamental concepts of transportation safety, including the background on transportation safety legislation; contributing factors of crashes; types of safety data; safety mitigation considerations; project prioritization; and policy development. This course emphasizes the need of multidisciplinary, collaborative efforts to improve safety from the many groups that are involved in transportation.

Courses 2, 3, 4, 8, and 12 teach about HSM safety analysis methods. All five of these courses familiarize participants with the purpose, structure, and benefits of the HSM while focusing on applying HSM methods to a specific application. New techniques to quantitative safety analysis that use SPFs and CMFs are introduced and utilized to predict the safety performance of various geometric design features. Participants learn how to evaluate and compare alternative designs based on safety performance.

Courses 5 and 11 are intended to teach practitioners how and when Interactive Highway Safety Design Model (IHSDM) software can be used in safety analysis. IHSDM is a suite of software analysis tools that checks a highway design against relevant design policy values and provides estimates of safety and performance for that design. The software suite is intended to support the decision making process in highway design. IHSDM software can be obtained for free from the IHSDM website (FHWA 2011). Both Courses 5 and 11 have the same content but Course 5 is presented in a traditional classroom setting while Course 11 is presented via online web-conferences.

Course 6 helps participants become familiar with components of HSIP and issues related to traffic and road safety. This course presents the latest methods for diagnosing crashes and selecting cost-effective countermeasures. This course is also a prerequisite for those who will be utilizing SafetyAnalyst, a software suite of highway safety analysis tools developed by FHWA and distributed by AASHTO (AASHTO 2011).

Course 7 presents low-cost, ready-to-use countermeasures that have proven to enhance highway safety. Participants will learn how to select appropriate countermeasures to address specific crash situations.

Courses 9 and 10 present information on CRFs (and CMFs). Course 9 focuses on applying CRFs for countermeasure selection while Course 10 focuses on evaluating the quality of CRFs through a review of CRF development methodologies. Both courses are online training courses utilizing web-conferences and self-paced learning activities.

Course 13, an HSM Workshop is currently under development and is expected to be offered beginning in April 2011.

Table 4-3. Recommended HSM Courses from NHI

	Course Title	Course Number	Training Level	Length	Cost per participant
1	Transportation Safety Planning	FHWA-NHI-151042	Intermediate	2 days	\$350
2	HSM Practitioners Guide for Geometric Design Features	FHWA-NHI-380070	Accomplished	2 days	\$400
3	HSM Practitioners Guide for Two-Lane Rural Highways	FHWA-NHI-380070A	Accomplished	1 day	\$300
4	HSM Practitioners Guide for Multilane Highways	FHWA-NHI-380070B	Accomplished	1 day	\$300
5	IHSDM	FHWA-NHI-380071	Accomplished	2 days	\$400
6	New Approaches to Highway Safety Analysis	FHWA-NHI-380075	Accomplished	3 days	\$500
7	Low-Cost Safety Improvements Workshop	FHWA-NHI-380076	Accomplished	1 day	\$300
8	HSM Practitioners Guide for Horizontal Curves	FHWA-NHI-380088	Intermediate	1 day	\$300
9	Application of CRFs	FHWA-NHI-380093	Intermediate	3 hours	\$90
10	Science of CRFs	FHWA-NHI-380094	Intermediate	2 hours	\$90
11	IHSDM Web Delivery	FHWA-NHI-380100	Accomplished	2 days	\$400
12	HSM Practitioners Guide for Intersections	FHWA-NHI-380105	Basic	1 day	\$300
13	HSM Workshop	FHWA-NHI-380106	-	-	-

Note: Courses current as of March 2011

4.3.3 ITE Safety Training Resources

ITE offers training courses and webinars from time to time that address highway safety and the HSM. During March 2011, ITE hosted four courses that addressed different aspects of the HSM. These courses are shown in Table 4-4. The cost per participant for the whole web series was \$350 for ITE members and \$455 for nonmembers.

Additionally, there was a full day seminar titled “A Practitioner’s Guide to the Highway Safety Manual” at the 2011 Technical Conference and Exhibit, which was held on April 3-6, 2011 in Lake Buena Vista, Florida. The target audience of the seminar was government and private sector transportation professionals involved in transportation and highway projects including designers, planners, traffic engineers and managers. Emphasis was placed on the application of the HSM for local transportation professionals by including example HSM applications and case studies. The content provided participants with a fundamental understanding of how HSM can be used to better evaluate, plan and program for safety improvements by integrating safety into all project development phases.

Table 4-4. ITE HSM Predictive Method Applications Webinar Series

	Course Title	Date	Course Content
1	Fundamentals of the HSM Predictive Method	3/22/2011	Introduces fundamental concepts of the HSM predictive method including: SPFs, CMFs, calibration factors, and the EB method.
2	Predicting Crash Frequency on Rural Highways	3/24/2011	Introduces the method and presents case study examples on applying the HSM predictive method for rural highways.
3	Predicting Crash Frequency on Urban and Suburban Arterials	3/29/2011	Introduces the method and presents case study examples on applying the HSM predictive method for urban and suburban arterials.
4	Applying HSM CMFs	3/29/2011	Introduces fundamentals of CMFs and provides case study examples of CMF applications

Note: Courses current as of March 2011

4.4 Chapter Summary

Rapid advances in highway safety methods and tools create potential for substantial improvement in highway safety; however, transportation officials and professionals must develop a working knowledge of these new methods and tools to be able to integrate them into practice. This chapter describes the efforts made by the TRB Task Force on Highway Safety Workforce Development to identify courses, sessions, and resources available for highway safety training. These efforts culminated in the creation of knowledge tables, which outline the specific needs and resources available to transportation professionals based on their role in the highway safety mitigation effort. Finally, selected training resources from FHWA, NHI, and ITE that address methods in the HSM were presented. The contents of this chapter will be beneficial to UDOT as they strive to further integrate safety into planning, design, operations, and maintenance activities.

THIS PAGE INTENTIONALLY LEFT BLANK

5 CONCLUSION

The purpose of this report is to aid UDOT in identifying and mitigating highway safety issues in the state of Utah. The preceding chapters developed a highway safety mitigation process based on the HSM Roadway Safety Management Process and provided recommendations on resources that can be used to improve safety workforce development.

This purpose of this chapter is to provide a summary and conclusions of the research, along with suggestions for future research.

5.1 Summary and Conclusions

Safety continues to be a high priority for UDOT. The research in this report series is part of an ongoing effort by UDOT to conduct transportation safety research that extends beyond the needs of today to address the needs of the transportation system of tomorrow. Safety analysis methods developed in the Volume 1 and Volume 2 reports can aid UDOT in the analysis of crash data. When applied within the framework for highway safety mitigation outlined in this report, these advanced methods of analysis can assist transportation officials in making better decisions regarding the investment of funds that will improve highway safety and ultimately save lives. Furthermore, this framework for highway safety mitigation along with appropriate safety workforce development resources will play a crucial role in enabling the next generation of transportation professionals to meet the highway safety needs of tomorrow.

The framework for highway safety mitigation presented in this report is based upon the HSM Roadway Safety Management Process and provides an overall process by which highway safety needs can be identified and mitigated in a cost-effective manner. This framework, summarized in Figure 5-1, consists of six steps: 1) network screening; 2) diagnosis; 3) countermeasure selection; 4) economic appraisal; 5) project prioritization; and 6) effectiveness evaluation. Incorporating state-of-the-art safety analysis methods within this framework allows

for improved assessment of roadway safety so that better decisions regarding highway safety investment can be made. Analysis methods developed in Volume 1 (Schultz et al. 2010) and Volume 2 (Saito et al. 2011) of this report series were discussed in the context of the appropriate step of the highway safety mitigation process.

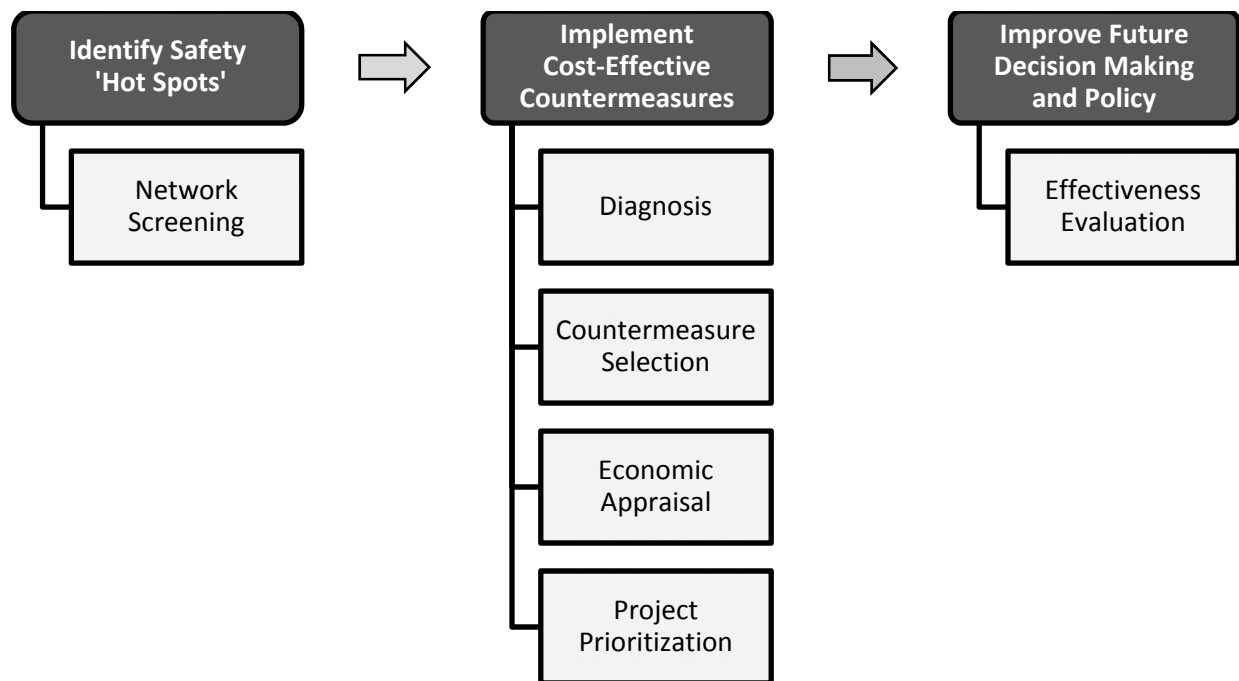


Figure 5-1. Framework for highway safety mitigation.

The effective application of this framework for highway safety mitigation requires transportation officials and professionals to understand the basis of highway safety analysis and mitigation. They must also understand how new methods of safety analysis can enhance their efforts to make efficient investment of highway safety improvement funds. Appropriate training can build these competencies. Therefore, recommendations on workforce development were provided in this report along with possible training opportunities offered by FHWA, NHI, and ITE. The training resources highlighted in this report encourage the integration of safety in the decision making process and the use of state-of-the-art safety analysis methods.

5.2 Suggestions for Future Research

Many specific components of the safety mitigation process could benefit from future research efforts. These efforts can help UDOT enhance their ability to identify sites with safety needs, select appropriate cost-effective countermeasures, and enhance future improvement efforts through safety effectiveness evaluation.

Additional research could enhance network screening methods to provide better identification of safety ‘hot spots.’ This research could involve using hierarchical Bayes analytical methods to improve the identification of locations where unusually high proportions of particular crash types occur on a statewide basis. Such research would aid UDOT with their federally mandated *5 Percent Report*. The network screening process could also be enhanced by developing GIS-based safety analysis to show the spatial relationship of safety ‘hot spots.’ These research efforts may also allow for the creation of operational safety reports describing overrepresented crash types at a given set of sites.

Connecting crashes with their corresponding hospital costs has potential to provide better estimates of the societal cost of crashes. BYU researchers are currently examining how crash databases and medical databases can be integrated to connect specific crashes with their corresponding hospital costs. This research has potential to provide better estimates of societal crash costs and improve the economic appraisal and prioritization of safety improvement projects.

The Volume 1 report develops a hierarchical Bayesian model to conduct safety effectiveness evaluations. Further research efforts could streamline conducting such studies and provide customizable reports on a variety of treatments. Furthermore, a framework for developing CMFs from this model could be created.

The Volume 2 report developed an HSM calibration factor and crash prediction models for Utah rural two-lane, two-way roads. These models were based solely on tangent roadway segments. These models could be improved by incorporating a larger dataset that includes curved roadway segments. Calibration factors and crash prediction models for other road types, such as rural multilane highways and urban and suburban arterials, could also be developed.

THIS PAGE INTENTIONALLY LEFT BLANK

REFERENCES

- American Association of State and Highway Transportation Officials (AASHTO). (2010). *Highway Safety Manual*. Washington, DC.
- American Association of State and Highway Transportation Officials (AASHTO). (2011). Safety Analyst home page. <www.safetyanalyst.org> (March 26, 2011).
- American Association of State and Highway Transportation Officials (AASHTO) Subcommittee on Safety Management. (2008). US Roadway Safety.org. <www.usroadwaysafety.org> (March 23, 2011).
- Chowdhury, M. A., Garber, N. J., and Li, D. (2000). Multi-objective Methodology for Highway Safety Resource Allocation. *Journal of Infrastructure Systems*, Vol. 6, No. 4. American Society of Civil Engineers, Reston, VA.
- Council, F. M., Zaloshnja, E., Miller, T., and Persaud, B. (2005). Crash Cost Estimates by Maximum Police Reported Injury Severity within Selected Crash Geometries, FHWA-HRT-05-051. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.
- Duval, T. D., and Gribbon D. J. (2008). "Memorandum to Secretarial Officers and Modal Officers: Treatment of the Economic Value of a Statistical Life in Departmental Analyses." Issued February 5, 2008, United States Department of Transportation, Washington, DC.
- Federal Highway Administration (FHWA). (2005). A Summary of Highway Provisions in SAFETEA-LU. <www.fhwa.dot.gov/safetealu/summary.htm> (March 26, 2011).
- Federal Highway Administration (FHWA). (2008). Guidance Memorandum on Consideration and Implementation of Proven Safety Countermeasures. <<http://safety.fhwa.dot.gov/policy/memo071008/>> (March 23, 2011).
- Federal Highway Administration (FHWA). (2011). Interactive Highway Safety Design Model (IHSDM) software download website. <<http://www.ihsdm.org>> (March 26, 2011).

- Gross, F., Persaud, B., and Lyon, C. (2010). A Guide to Developing Quality Crash Modification Factors, FHWA-SA-10-032. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.
- Haddon, W. (1972). A Logical Framework for Categorizing Highway Safety Phenomena and Activity. *The Journal of Trauma*, Vol. 12. Lippincott Williams & Wilkins, Philadelphia, PA.
- Hauer, E. (1997). *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*, Pergamon, Oxford UK.
- Hauer, E., Harwood, D. W., Council, F. M., and Griffith, M. S. (2002). “Estimating Safety by the Empirical Bayes Method: A Tutorial.” *Transportation Research Record: Journal of the Transportation Research Board*. 1784, Transportation Research Board, National Research Council, Washington, DC, 126-131.
- Herbel, S., Laing, L., and McGovern, C. (2010). Highway Safety Improvement Plan (HSIP) Manual, FHWA-SA-09-029, Federal Highway Administration, Washington, DC.
- Hunter, W. W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M., Harkey, D. L. (2001). “Three-Strand Cable Median Barrier in North Carolina”. *Transportation Research Record: Journal of the Transportation Research Board*. 1743, Transportation Research Board, National Research Council, Washington, DC, 97-103.
- Mclanahan, D., Albin, R. B., Milton, J. C. (2003). “Washington State Cable Median Barrier In-Service Study.” Compendium of the Transportation Research Board 83rd Annual Meeting, Transportation Research Board, National Research Council, Washington, DC.
- National Cooperative Highway Research Program (NCHRP). (1998). *National Cooperative Highway Research Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*. NCHRP, Transportation Research Board, National Research Council, Washington, DC.
- National Highway Institute (NHI). (2011). Introduction to the National Highway Institute. <www.nhi.fhwa.dot.gov/about/intro_nhi.aspx> (March 26, 2011).
- National Highway Traffic Safety Administration (NHTSA). (2008). Model Minimum Uniform Crash Criteria. <www.mmucc.us> (March 26, 2011).
- National Highway Traffic Safety Administration (NHTSA). (2010). Countermeasures that Work: A Highway Safety Countermeasure Guide for State Highway Safety Offices, 5th Edition, DOT-HS-811-258, National Highway Traffic Safety Administration, Washington, DC. <<http://www.ghsa.org/html/publications/countermeasures/index.html>> (March 29, 2011).

- National Safety Council (NSC). (2007). Manual on Classification of Motor Vehicle Traffic Accidents, 7th Edition, Itasca, IL.
- Olsen, A. N., Schultz, G. G., Thurgood, D. J. and Reese, C. S. (2011). "Hierarchical Bayesian Modeling for Before and After Studies." *Compendium of the Transportation Research Board 90th Annual Meeting*, Transportation Research Board, National Research Council, Washington, DC.
- Qin, X., Ivan, J. N., and Ravishanker, N. (2004). "Selecting Exposure Measures in Crash Rate Prediction for Two-Lane Highway Segments." *Accident Analysis and Prevention*, 36(2), 183-191.
- Roop, S. S., and Mathur S. K. (1995). Development of a Multimodal Framework for Freight Transportation Investment: Consideration of Rail and Highway Tradeoffs, Final Report of NCHRP Project 20-29. Texas A&M University, College Station, TX.
- Saito, M., Schultz, G. G., Brimley, B. K. (2011). "Transportation Safety Data and Analysis, Volume 2: Calibration of the Highway Safety Manual and Development of New Safety Performance Functions, UT-10.12b, Utah Department of Transportation Traffic and Safety, Research Divisions, Salt Lake City, UT.
- Schultz, G. G., Thurgood, D. J., Olsen, A. N., and Reese, C.S. (2010). "Transportation Safety Data and Analysis, Volume 1: Analyzing the Effectiveness of Safety Measures using Bayesian Methods, UT-10.12a, Utah Department of Transportation Traffic and Safety, Research Divisions, Salt Lake City, UT.
- Schultz, G. G., Thurgood, D. J., Olsen, A. N., and Reese, C.S. (2011). "Analyzing Raised Median Safety Impacts using Bayesian Methods." *Compendium of the Transportation Research Board 90th Annual Meeting*, Transportation Research Board, National Research Council, Washington, DC.
- Transportation Research Board (TRB) (2010). Task Force on Highway Safety Workforce Development (ANB23T). Highway Safety Training Synthesis/Roadmap, Working Paper 2, HR 20-7(290), NCHRP, Transportation Research Board, National Research Council, Washington, DC.
- Transportation Research Board (TRB) (2011). Status of NCHRP 20-07/Task 290. <[http:// 144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2866](http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2866)> (April 27, 2011)
- Treat, J. R., Tumbas, N. S., McDonald, S. T., Dhinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., and Castellan, N. J. (1979). Tri-level Study of the Causes of Traffic Crashes: Final Report Executive Summary, DOT-HS-034-3-535-79-TAC(S), Institute for Research in Public Safety, Bloomington, IN.

Utah Department of Transportation (UDOT). (2009). UDOT Roadway Safety Improvement Program: Utah's Implementation of the Federal Highway Safety Improvement Program. Utah Department of Transportation, Division of Traffic and Safety, Salt Lake City, UT.

Utah Department of Transportation (UDOT). (2011a). 5% Report of Safety Needs: Fiscal Year 2010 Annual Report. <www.udot.utah.gov/main/uconowner.gf?n=13651927612454382> (March 26, 2011).

Utah Department of Transportation (UDOT). (2011b). Highway Safety Improvement Program (HSIP). <www.udot.utah.gov/main/f?p=100:pg:0::::T,V:2933> (March 26, 2011).

LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State and Highway Transportation Officials
BCR	Benefit-Cost Ratio
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
DOT	Department of Transportation
DP	Dynamic Programming
EB	Empirical Bayes
EPDO	Equivalent Property Damage Only
FHWA	Federal Highway Administration
GIS	Geographic Information System
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
IMRA	Interactive Multi-objective Resource Allocation
IP	Integer Programming
ITE	Institute of Transportation Engineers
LP	Linear Programming
MCCBA	Multicriteria Cost-Benefit Analysis
MPO	Metropolitan Planning Organization
NCHRP	National Cooperative Highway Research Program
NHI	National Highway Institute
NHTSA	National Highway Traffic Safety Administration
NPV	Net Present Value
NPW	Net Present Worth
PDO	Property Damage Only

RTM	Regression to the Mean
SAFETEA-LU	The Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Function
TRB	Transportation Research Board
UDOT	Utah Department of Transportation