Review and Enhancement for Crash Analysis and Prediction: Phase 1 Evaluation of the Crash Studies and Analysis Standard Operating Procedures in Maryland

MID-ATLANTIC UNIVERSITIES TRANSPORTATION CENTER

MAUTC

Region III

Pennsylvania State University ❖ University of Maryland University of Virginia
❖ Virginia Polytechnic Institute and State University
West Virginia University

The Pennsylvania State University ❖ The Thomas D. Larson Pennsylvania Transportation Institute
Transportation Research Building ❖ University Park, Pennsylvania 16802-4710
Phone: 814-863-1909 ❖ Fax: 814-863-3707
www.pti.psu.edu/mautc

Review and Enhancement for Crash Analysis and Prediction:
Phase 1-Evaluation of the Crash Studies and Analysis Standard Operating Procedures in Maryland

Final Report

To

Office of Policy and Research
Maryland State Highway Administration

707 N. Calvert Street
Baltimore, MD 21202

by

Dr. Gang-Len Chang, Professor
gang@umd.edu
Dr. Jie Yu and Dr. H. W. Ho, Assistant Research Scientists
Department of Civil Engineering
The University of Maryland
College Park, MD 20742

March 2010

1. Report No. UMD-2007-03	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle REVIEW AND ENHANCEMENTFOR CRASH ANALYSIS AND PREDICTION: PHASE 1-EVALUATION OF THE CRASH STUDIES AND ANALYSIS STANDARD OPERATING PROCEDURES IN MARYLAND	**5. Report Date** March 2010
	6. Performing Organization Code
7. Author(s) Dr. Gang-Len Chang, Dr. Jie Yu and Dr. H. W. Ho	**8. Performing Organization Report No.** UMD-2007-03
9. Performing Organization Name and Address Department of Civil Engineering The University of Maryland College Park, MD 20742	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. DTRS99-G-003
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration UTC Program, RDT-30 1200 New Jersey Ave., SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Traffic safety has become one of the most critical issues facing transportation agencies across the nation. In 2006, about 43,000 people were killed, and another 290,000 were seriously injured in crashes on public roadways in the United States. According to a study by the American Automobile Association, traffic crashes in urban areas cost $164 billion in 2005, including the costs of property damage, lost earnings, medical treatment, emergency services, pain and lost quality of life, and other costs

17. Key Words Traffic Safety, American Automobile Association	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 54	**22. Price**

Technical Report Documentation Page

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

TABLE OF CONTENTS

TABLE OF CONTENTS i

CHAPTER 1 INTRODUCTION 1

1.1 RESEARCH BACKGROUND 1

1.2 RESEARCH OBJECTIVES 2

1.3 REPORT ORGANIZATION 2

CHAPTER 2 OVERALL RESEARCH FRAMEWORK 4

2.1 INTRODUCTION 4

2.2 RESEARCH TASKS AND OVERALL FLOWCHART 5

2.3 CONCLUSION 8

CHAPTER 3 SCREENING OF HIGH-CRASH LOCATIONS 9

3.1 INTRODUCTION 9

3.2 MARYLAND PROCEDURES 9

3.3 SAFETYANALYST PROCEDURES 13

3.4 METHODS USED BY OTHER STATES 17

3.5 RECOMMENDATIONS 24

CHAPTER 4 COST/BENEFIT ANALYSIS 26

4.1 INTRODUCTION 26

4.2 MARYLAND PROCEDURES FOR COST/BENEFIT ANALYSIS 26

4.3 SAFETYANALYST PROCEDURES 29

4.4 PROCEDURES USED BY THE STATE OF INDIANA 32

4.5 RECOMMENDATIONS 36

CHAPTER 5 COUNTERMEASURE EVALUATION 37

5.1 INTRODUCTION 37

5.2 MARYLAND PROCEDURES 37

5.3 PROCEDURES USED IN SAFETYANALYST 40

5.4 PROCEDURES BY OTHER STATES 43

5.5 RECOMMENDATIONS 44

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS 46

6.1 SUMMARY OF RESEARCH FINDINGS 46

6.2 CONCLUSION 47

REFERENCES 49

APPENDIX- I: THE REGRESSION-TO-THE-MEAN PROBLEM 51

APPENDIX- II: THE EMPIRICAL BAYESIAN (EB) APPROACH 53

CHAPTER 1 INTRODUCTION

1.1 RESEARCH BACKGROUND

Traffic safety has become one of the most critical issues facing transportation agencies across the nation. In 2006, about 43,000 people were killed, and another 290,000 were seriously injured in crashes on public roadways in the United States. According to a study by the American Automobile Association, traffic crashes in urban areas cost $164 billion in 2005, including the costs of property damage, lost earnings, medical treatment, emergency services, pain and lost quality of life, and other costs (GAO, 2008).

In recent years, federal, state and local transportation/highway agencies have increasingly dedicated themselves to introducing policies and practices for improving safety and efficiency of transportation systems. The Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), which was enacted on August 10, 2005, established the Highway Safety Improvement Program (HSIP) as a core federal-aid program (FHWA, 2008). The purpose of this program is to achieve a significant reduction in traffic fatalities and serious injuries on all public roads through the implementation of infrastructure-related highway safety improvements. In an effort to provide a safe highway system to users and to take maximum advantage of available federal safety funding, the Maryland State Highway Administration (MDSHA) has developed standard operating procedures (SOPs) for HSIP that consists of four components: 1) development and implementation of a Strategic Highway Safety Plan (SHSP) that identifies and analyzes highway safety problems and the potential for reducing fatalities and serious injuries; 2) production of projects or strategies to reduce identified safety problems; 3) evaluation of the proposed plans on a regular basis to ensure the accuracy of the data and the priority of improvements; and 4) submission of an annual report to the Federal Highway Administration (FHWA) (MDSHA, 2007a).

Well-designed SOPs could effectively help identify the locations for implementing safety measures. However, the lack of an in-depth study of critical issues in the SOPs could lead to decisions that fail to alleviate, or even exacerbate, existing traffic safety problems. It is, therefore, imperative to evaluate the current SOPs and to identify potential improvements to better assist traffic professionals in enhancing highway safety.

1.2 RESEARCH OBJECTIVES

The primary objective of this study is to identify the deficiencies of current crash studies and analysis SOPs in Maryland and to recommend possible improvements. This study will focus on the following critical issues:

- Can the current procedures for determining candidate locations for safety improvement truly identify the high-risk locations?
- Does the current method for cost/benefit analyses effectively prioritize different improvement plans?
- Can the current methodology for before/after studies reliably measure the effectiveness of different improvement plans?

The research results with respect to the above issues will offer the basis for SHA to: (1) better understand the strengths and weaknesses of the current SOPs and to minimize the cost associated with its implementation; and (2) define potential directions for improving the SOPs.

1.3 REPORT ORGANIZATION

Based on the research objectives, this study has organized all primary results and key findings into the five subsequent chapters. A brief description of the information contained in each chapter is presented below.

Chapter 2, after providing an overview of the current crash studies and analysis SOPs in Maryland, illustrates the overall research framework and outlines critical project tasks, along with major activities.

Chapter 3 offers a comprehensive comparison of available methods for screening high-crash locations, based on an in-depth review of the procedures adopted in Maryland and other states. The chapter also presents recommendations for improving Maryland's currently adopted methodology for screening high-crash locations.

Chapter 4 reviews the procedures for cost/benefit analyses adopted by the Maryland SHA, SafetyAnalyst and other states. This chapter also includes recommendations for potential improvements.

Chapter 5 presents a review of state-of-the-art and state-of-the-practice studies associated with the countermeasure evaluation procedures adopted by the Maryland SHA, SafetyAnalyst, and other states. This chapter also describes potential improvements to overcome some deficiencies identified in the current Maryland countermeasure evaluation for crash studies and analysis.

Overall research findings and future research needs constitute the core of the final chapter.

CHAPTER 2 OVERALL RESEARCH FRAMEWORK

2.1 INTRODUCTION

In an effort to reduce the number of crashes, traffic fatalities, and serious injuries on public roads, Congress passed and President Bush signed SAFETEA-LU in August 2005. The Act nearly doubled the amount of federal funding for the HSIP by authorizing $5.1 billion from 2006 through 2009 (GAO, 2008). To ensure that the HSIP is carried out in an organized and systematic manner to achieve the most benefits, the FHWA established a formalized HSIP process (FHWA, 2008), consisting of three major components: planning, implementation, and evaluation (Figure 2-1).

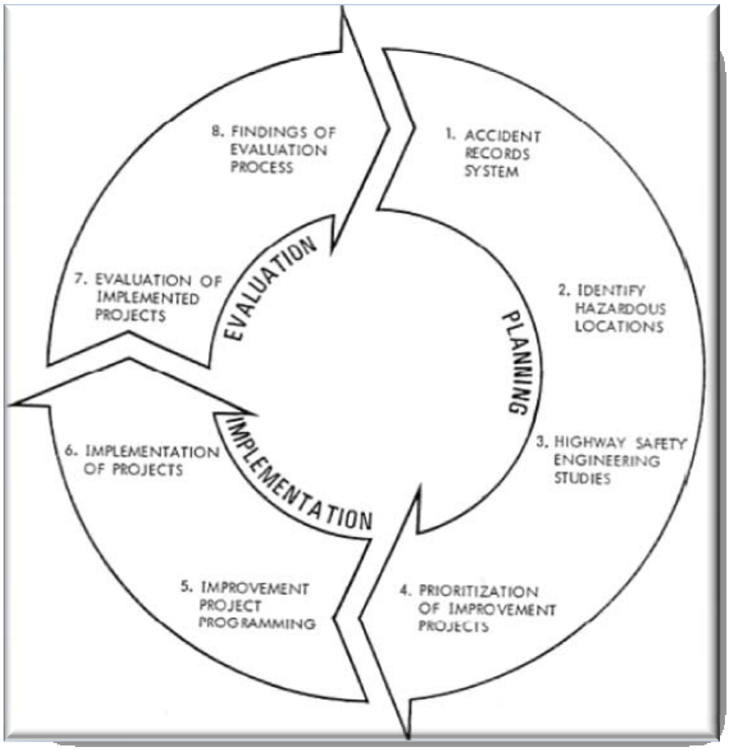

Figure 2-1 Formalized HSIP process

(Source: Seyfried, 2008)

In response to federal requirements (FHWA, 2008), the Maryland SHA has developed a statewide HSIP to improve the safety of highway intersections, segments, and ramps that have been identified as Candidate Safety Improvement Locations (CSIL). The overall SOPs are illustrated in Figure 2-2 (MDSHA, 2007a).

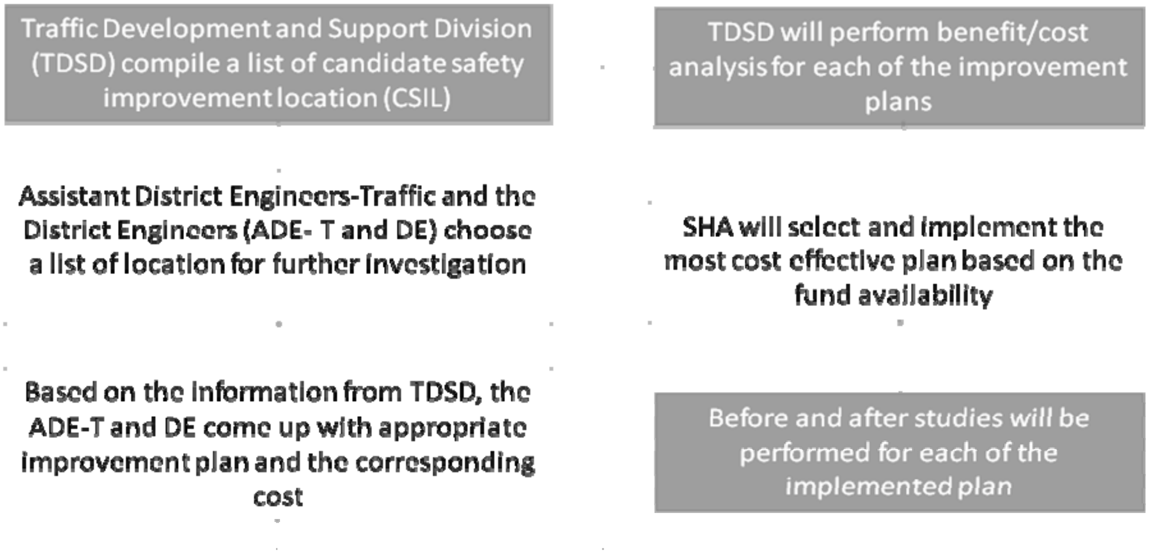

Figure 2-2 Overall SOPs in Maryland's HSIP

This research will focus on comparing the procedures used by the Maryland SHA in planning and evaluating safety improvement plans with those adopted by other states and the federal government.

This chapter is organized as follows: Section 2.2 divides the research work into four tasks and reports the critical issues associated with each task. Section 2.3 summarizes the comments on the overall research framework.

2.2 RESEARCH TASKS AND OVERALL FLOWCHART

To complete the research objectives outlined in Chapter 1, the study has focused on the following tasks:

Task 1: *Performing an in-depth review of the current procedures for identifying high-crash locations and for evaluating effectiveness of safety improvement plans.*

Task 2: *Identifying the embedded deficiencies of the current crash studies and analysis SOPs.*

Task 3: *Recommending improvements to the current crash studies and analysis SOPs.*

Task 4: *Producing technical reports and holding workshops to highlight research findings.*

Figure 2-3 shows the overall research flowchart. A brief description of each task is presented below:

Task 1: Performing an in-depth review of the current procedures for identifying high-crash locations and for evaluating the effectiveness of safety improvement plans

In performing this task, the research team will extensively review the currently adopted procedures from the following institutes:

a) Maryland SHA;
b) FHWA; and
c) similar procedures available from other states.

The review will focus on the following critical issues:

a) criteria for screening and sorting high-crash locations;
b) indicators used to quantify the effectiveness of safety improvement plans;
c) assumptions made in the procedures; and
d) types and sources of data required for the evaluation.

Task 2: Identifying the deficiencies of the current crash studies and analysis SOPs.

The criteria adopted in this task for identifying the deficiencies in the procedures used by the Maryland SHA are summarized below:

a) Effectiveness and efficiency — Used to measure the effectiveness of the Maryland SOPs in identifying high-crash locations and to evaluate safety improvement plans.
b) Theoretical and/or statistical support — Used to measure the soundness of the theoretical basis underlying the currently adopted SOPs.
c) Reasonableness of assumptions made.
d) Practicality — This refers to data needs and required staff skills.

Using these criteria, this task will report on the areas in the current Maryland SOPs that need some improvement.

Task 3: Recommendations for possible improvements in the current crash studies and analysis SOPs

This task focuses mainly on recommending methods for improving Maryland's current crash studies and analysis SOPs. The recommended methods shall overcome some or all the deficiencies identified in Task 2. The areas of potential improvement include:

a) Procedures for screening and sorting the high-crash locations.
b) Procedures for cost/benefit analyses.
c) Procedures for before/after studies.

The recommendations made in this task will include possible methods for improving the data, as well as detailed mathematical procedures for implementation.

Task 4: Producing technical reports and conducting workshops to highlight research findings.

After the annual list of high-crash locations has been generated and evaluated along with the current crash studies and analysis SOPs, it is important to ensure that potential users know the embedded deficiencies. Therefore, it is essential to document the findings and recommendations from this study. The research team will perform the following activities during this final task:

a) Present research findings and recommendations to SHA staff at technical workshops; and
b) Document research findings and recommendations in a technical report.

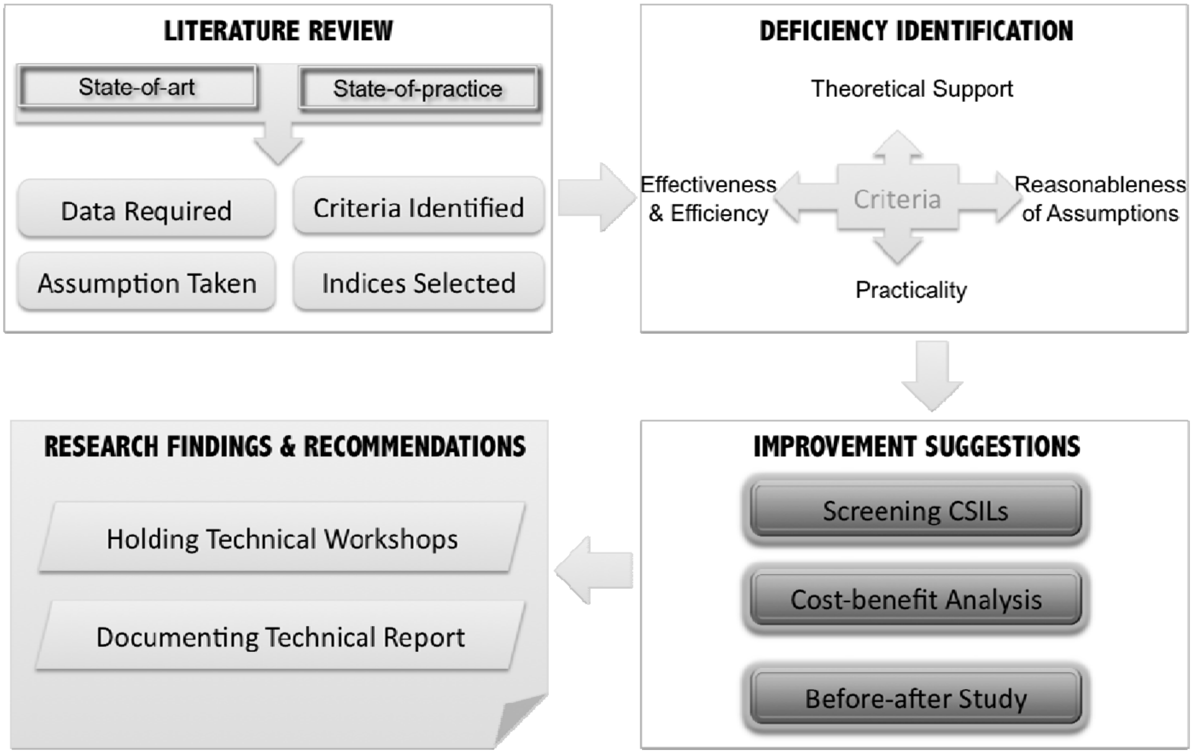

Figure 2-3 Overall research flowcharts

2.3 CONCLUSION

This chapter illustrates the key research tasks and critical issues to be addressed in this study. The remaining chapters will present our research results from each task in sequence. We will review and compare the deficiencies and strengths of all available methods documented in the literature for crash studies to those adopted by the Maryland SHA.

CHAPTER 3 SCREENING OF HIGH-CRASH LOCATIONS

3.1 INTRODUCTION

In recent years, FHWA, along with several state and local transportation agencies, has devoted tremendous resources to developing state-of-the-art analytical tools, namely SafetyAnalyst, for use in identifying and managing a system-wide program to enhance highway safety. In addition, the HSIP requires each state to submit an annual report that describes not less than 5 percent of its highway locations that need the most safety improvements. States are required to identify and rank hazardous locations on all public roads, as measured by the relative severity of the fatalities and injuries at those locations.

This chapter will offer a comprehensive comparison of available methods for screening high-crash locations, including Maryland's procedures, the SafetyAnalyst procedures, and similar methods from other states. The next section will first briefly introduce the methods used by the Maryland SHA; then Section 3.3 will present four types of screening and ranking procedures provided by SafetyAnalyst, along with their pros and cons. This will be followed by an extensive summary of procedures used by other states in Section 3.4. Concluding comments and recommendations are reported in the last section.

3.2 MARYLAND PROCEDURES

Note that, in applying the Maryland procedure (MDSHA, 2007a), one needs to classify all candidate locations into two distinct categories (sections and intersections), and then apply the recommended procedures for screening and ranking locations in each category. A detailed description of the procedures for each type of location is presented below:

3.2.1 *Procedures for Ranking Roadway Sections*

The sliding scale program, the principal method for defining the candidate sections for screening and ranking, takes a section of 0.5 mile with a sliding window of every 0.01 mile as the basis for measurement. The procedures for the sliding program are as follows:

a) Take the statewide average crash density (in crashes per mile) as the minimum cut-off point;
b) Select those sections with more crashes than the minimum cut-off point, and form the list of Candidate Safety Improvement Sections (CSISs);

c) Compute the crash rate (in crashes per 100 million vehicle miles) by using the traffic volume data;

d) Compute the upper control value for each CSIS location, using Donald A. Morin's Rate Quality Control Method. A location with a crash rate of twice this upper control value is considered a priority safety improvement section (PSIS).

Candidate sections are screened and ranked using a three-year combined CSIS list for analysis, due to the relative low frequency of crashes.

The main advantage of this screening and ranking method lies in its use of only observed crash frequency and volume data. Hence, one can complete its required procedures with minimal resources. However, this method for screening and ranking hazardous roadway sections suffers the following embedded deficiencies:

a) Using the *statewide average crash density* as the cut-off in the first step introduces a *bias toward high-volume locations*. This is due to the fact that crash densities are usually lower for locations with low traffic volumes, since the number of crashes is directly proportional to the traffic volume. As a result, the candidate list generated by such a method may miss some potentially hazardous locations in low-volume areas and include some less critical locations in high-volume areas (See Figure 3-1);

b) Using this *fixed-length sliding scale program may neglect corridor-wide safety problems*. This method considers crash density separately for each section. Thus, if the crash density for a target section is less than the cut-off value, the location will not be short-listed despite the existence of a safety problem at the corridor level.

c) Using the three-year *observed crash frequency neglects natural fluctuations in crash frequencies* (See Figure 3-2) and suffers from so called "*regression to the mean errors*" (discussed in Appendix I), in which an unusually high frequency is likely to decrease subsequently, even if no improvement was implemented. Therefore, a site with such a crash frequency may not need improvement. Conversely, a truly hazardous site may have a randomly low observed count of crashes and therefore escape detection.

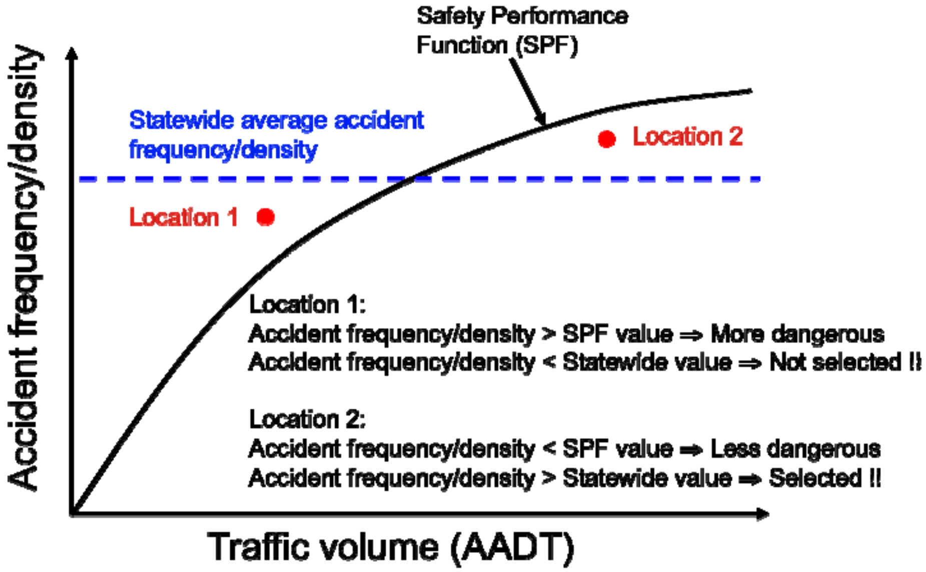

Figure 3-1 Use of statewide average crash frequency/density

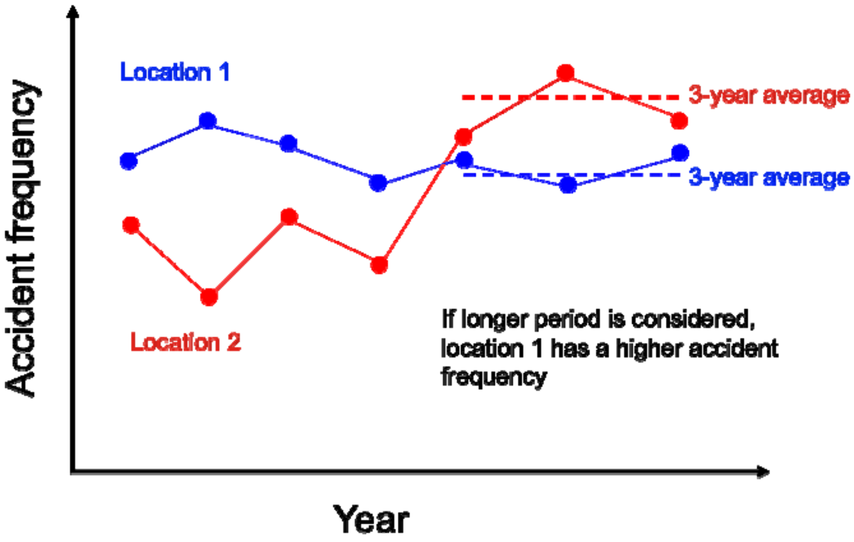

Figure 3-2 Fluctuation of crash frequency

3.2.2 *Procedures for Ranking Intersections*

Crash frequency, rate, and severity are used sequentially to screen and rank the candidate set of intersections. The entire procedure includes the following steps:

a) Find a crash frequency that is higher than the average value, using the *countywide average crash frequency* of a particular type of intersection and assuming a Poisson distribution for all crashes.

b) Double this frequency to set the cut-off number for identifying the list of the candidate safety improvement intersections (CSIIs).

c) Compute the *crash rate* for each CSII location — dividing the number of crashes observed by half of the AADT (Average Annual Daily Traffic) entering the intersection — for further screening.

d) Identify an intersection as one of the priority safety improvement intersections (PSIIs) if its crash rate is higher than or equal to 1 accident/MVE (million vehicles entering the intersection); further rank those locations on the PSII list with their respective crash rates.

e) Assign the following weights to compute the severity rate for each location on the PSII list: fatality = 5; incapacitating injury = 4; non-incapacitating injury = 3; possible injury = 2; property damage only = 1.

f) Use the computed severity rate to prioritize the locations with the same crash rate, and also to sort out the locations with crash rates less than one crash per MEV but having a high severity rate.

Note that, although the above procedures for screening and ranking hazardous intersections are relatively long, they have the following advantages: (a) using the crash frequency, crash rate, and severity rate to screen and rank the candidate locations provides a more comprehensive comparison than using only one indicator; (b) the stepwise screening procedures could effectively reduce the number of locations to be evaluated in subsequent steps, thus minimizing the workload needed for the evaluation process.

Despite the above advantages, the screening and ranking results from this procedure may suffer from the following estimation biases:

a) All candidate locations are screened using only the observed crash frequency; regression to the mean errors are likely to exist in the estimation results. Moreover, those locations with severe crashes may not be screened out if they have a low crash frequency.

b) If the crash rates are computed with the observed counts, then the regression to the mean biases discussed above will also exist. Moreover, the relationship between crash frequency and AADT is not linear (MRI, 2002). As Figure 3-3 shows, the crash rate (the slope of a line from the origin to a point on the curve) is expected to be lower at locations of higher traffic volume. Thus, using the crash rate as the second screening criterion tends to yield a list of locations with low volume, regardless of their actual level of hazard.

c) The assumptions involved in assigning a weight to each severity level is somewhat arbitrary and cannot reflect the relative impact of different severity levels.

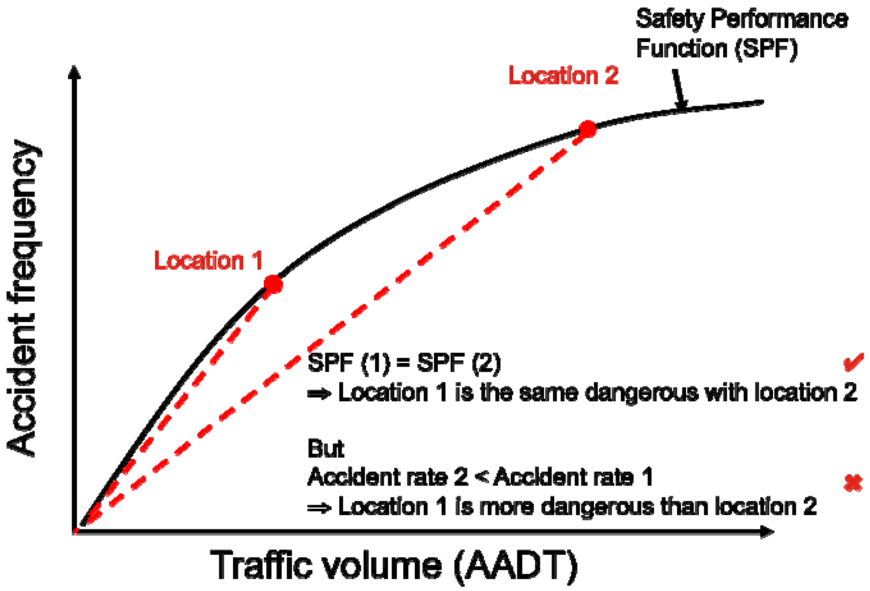

Figure 3-3 Use of crash rate

3.3 SAFETYANALYST PROCEDURES

The SafetyAnalyst software (FHWA, 2006) incorporates a set of state-of-the-art safety analysis approaches to guide the process of identifying safety improvement needs and developing a systemwide program of site-specific improvement projects. SafetyAnalyst classifies locations into sections, intersections, and ramps. It includes the following four types of screening and ranking procedures:

- Basic network screening
- High proportion of a specific crash type
- Screening for safety deterioration
- Corridors with promise

The core logic associated with each type of procedure is summarized in sequence below:

3.3.1 *Basic Network Screening with Potential Safety Improvement (PSI)*

The basic network screening methodology uses an empirical Bayesian (EB) methodology to predict the potential for safety improvement (PSI) at a candidate site. In SafetyAnalyst, the PSI could be defined as the following forms (see Figure 3-4):

a) *Expected crash frequency* — The EB-adjusted crash frequency, based on the observed crash frequency of that location and the value calculated from the safety performance function (SPF) for this type of location (see Appendix II).

b) *Excess crash frequency* — The difference between the EB-adjusted crash frequency and that predicted by the SPF function.

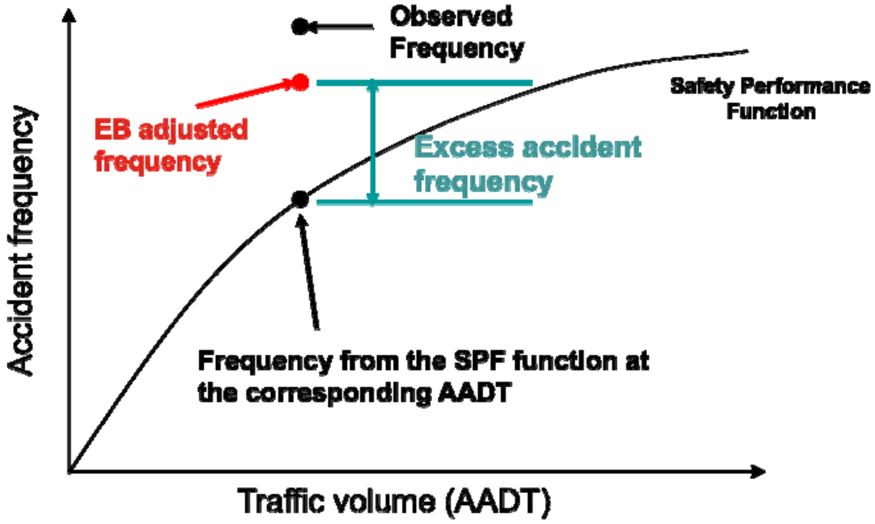

Figure 3-4 Definition of EB-adjusted frequency and excess crash frequency

Note that, compared with the commonly-used indicators (i.e., observed crash frequency/ density/rate), the proposed PSI can recognize the nonlinear relationship between crash frequency and AADT and can also alleviate the regression to mean biases, as the crash frequency of each candidate site is adjusted with the average crash frequency of similar sites. However, calibrating the SPF to generate the PSI requires the use of extensive data and complex computing procedures.

Procedures for Screening and Ranking with PSI

SafetyAnalyst offers the following two methods (intersections or ramps) for screening and ranking candidate locations with PSI:

a) *Peak searching method* — This method divides a target site into a number of windows to cover the entire site. For each window, the expected crash frequency (or excess crash frequency) is calculated on a per mile basis. Based on the statistical significance of the expected value, the maximum expected crash frequency (or excess crash frequency) across all windows within a roadway segment is used to rank the PSI of that site relative to the other sites in the candidate list**.**

b) *Sliding window method* — The sliding window approach uses a window of user-specified length as the unit of analysis. This window is incrementally moved along contiguous roadway segments (sites) of a unique route in the highway system, overlapping previous windows if the incremental length is less than the window length. Since a window does not necessarily end at the end of a site, window locations may bridge most, but not all, contiguous roadway segments. At each window location, the expected crash frequency (or excess crash frequency) is calculated on a per mile basis. The maximum expected crash frequency (or excess crash frequency) across all windows pertaining to a roadway segment is used to rank the PSI of that site relative to the other sites within the site list. A window is viewed as pertaining to a given site if at least some portion of the window is within the boundaries of the target site.

Note that the sliding windows method adopted in SafetyAnalyst differs from the Maryland procedure in that it allows the evaluation windows to slide across the adjacent roadway sections (i.e., one portion of sliding window could be in the previous section while the other is in the next section). Having sliding windows placed across two neighboring sections could effectively check whether abnormally high crash frequencies at such locations are due to changes in section characteristics that may not be easily detected by considering the two sections independently.

Comparing the two screening methods, the peak searching approach incorporates statistical procedures to improve the reliability of the results, while the sliding window technique applies EB concepts in a more traditional fashion to screen roadway segments. In other words, the sliding window approach only tests whether the expected crash frequency is greater than or less than a preset value, while the peak searching approach tests for both the magnitude of the expected value and the statistical reliability of the estimate. Therefore, the peak searching approach is a slightly more rigorous screening methodology.

3.3.2 *Procedures for Screening for a High Proportion of a Specific Crash Type*

The objective of this screening method is to identify sites that have a higher proportion of a target crash type than expected and to rank those sites based on the difference between the observed and the expected proportions of crashes. The methodology is based only on proportions of total target crashes of a specific type and allows the list to include all location types (i.e., road segments, intersections, and ramps). The entire procedure includes the following three steps:

a) Calculate the observed proportion of the total accidents for the specific target crash type;
b) Calculate the probability that the observed proportion is greater than the specified proportion limit (i.e., average for site and crash type);
c) Flag a target site when its associated probability is greater than some user-specified significance level.

The need for such a screening method arises from the fact that many locations may have relatively low crash frequencies but can be effectively treated with countermeasures due to their well-defined crash patterns. The most significant advantage of this screening procedure lies in its striving to identify locations having an overrepresentation of particular types of crashes, which may facilitate the selection of countermeasures and identify locations that are good candidates for cost-effective treatment.

3.3.3 *Procedures for Screening for Safety Deterioration*

The objective of this screening methodology is to identify sites where the mean crash frequency has increased over time to more than can be attributed to changes in traffic volume or general trend. This screening methodology may be applicable to all site types (i.e., road segments, intersections, and ramps), as it is based strictly on the total crashes. The basic concept of this methodology is that when the average crash frequency for a site in recent years appears significantly larger than in preceding years, there is sufficient reason to examine the site in more detail. Both steady and sudden increases in crash frequency are detected with a statistical test for the difference between the means of two Poisson random variables. The procedures proposed by Hauer (2007) are suggested for analyzing each time series of crash counts for this method.

Note that one unique feature of this screening methodology is that sites are identified for their potential for safety improvement. With this screening approach, sites "testing positive" are flagged for investigation but are not ranked. The number of sites flagged depends on the stringency of the testing criteria. The user may select the criteria by trial and error so as to obtain a manageable number of flagged sites.

3.3.4 ***Procedures for Corridors with Promise for Safety Improvement***

For the corridor-level analysis, one needs to aggregate all sites to investigate the crash history of a group of roadway segments, including intersections, and/or ramps. Thus, sites with a common corridor number are analyzed as a single entity. The user has the option to rank corridors by one or both of the following two basic measures:

a) *Crashes/mi/yr*: the crash frequency on a per mile basis;
b) *Crashes/mvmt/yr:* the crash rate (*per million vehicle miles of travel*) on a per mile basis.

Calculations of these two measures are based on observed crashes. In addition, the methodology is based strictly on the total number of crashes. Note that the procedures proposed by SafetyAnalyst for screening corridors differ significantly from all three other screening and ranking procedures, which are performed on a site-by-site basis. Its second detecting measure, *crashes/mvmt/yr*, takes into account the traffic volume exposure in evaluating the safety potential of a site (e.g., corridor), and thus could give a more objective estimation of hazard than the first measure, *crashes/mi/yr*. This is due to the fact that comparing crash frequencies between two corridors is not meaningful unless both experience the same level of exposure.

3.4 METHODS USED BY OTHER STATES

The review results reported in this section are based on the Five Percent reports submitted by individual state to the FHWA over the last few years (2006 to 2008), as well as supplemental documents obtained from published references (FHWA, 2008; Dixon and Monsere, 2007; Pawlovich, 2007; Seyfried, 2008).

To facilitate the presentation, this section has classified all state-of-the-practice methods into the following four categories:

- Simple methods:
  - Crash frequency
  - Crash density
  - Crash rate
- Crash severity methods:
  - Equivalent Property-Damage-Only (EPDO) method
  - Relative Severity Index (RSI) method
- Quality control methods:
  - Number Quality Control method
  - Rate Quality Control method
- Composite methods:
  - Frequency-rate method
  - Weighted Rank method
  - Crash Probability Index (CPI) method

A brief review of each available method’s pros and cons is presented below:

3.4.1 *Procedures of Simple Methods*

All methods classified in this category employ one of the following three indicators in performing the analysis:

a) *Crash frequency*: defined as the number of crashes for a given location.

b) *Crash density*: denotes the number of crashes per mile for highway sections.

c) *Crash rate*: computed from the number of crashes per million vehicle miles traveled for road segments or, for intersections, the number of crashes per million vehicles entering.

A jurisdiction may identify one candidate location as being at the critical level if any of its above three indicators exceeds a predetermined threshold.

All methods in this category are noticeably quite straightforward and need only the data of number of crashes, length of section (for crash density), and location to perform the analysis. Such methods, however, do not take into account the factor of exposure to traffic volume. For example, locations may have high crash frequencies simply because of high traffic volume conditions rather than because of physical roadway characteristics. Therefore, the crash frequency and crash density methods tend to rank high-volume locations as high-crash locations, even if the relative number of crashes is low given their volume. Moreover, as mentioned in Section 3.2.1, if the number of crashes observed short-term is used as input information, fluctuations of crash frequencies/densities will be neglected and regression to the mean errors will exist.

Unlike the crash frequency and crash density methods, the use of crash rate includes exposure to traffic volume in the evaluation process. Hence, it does not have the bias toward selecting high-volume locations that is observed with the crash frequency approach. The crash rate method, however, tends to produce a high crash rate at low-volume locations, resulting in a bias toward low-volume locations, as shown in Figure 3-3.

Note that all of the aforementioned methods use crash types rather than severity data, such as injuries or fatalities. Therefore, the final locations identified with any of the above measures are unlikely to be the most hazardous locations as regards crash severity.

3.4.2 *Crash Severity Methods*

The crash severity methods utilize a variety of indicators to incorporate severity measures, including the frequency/density of more severe crashes, the rate of more severe crashes, and the ratio of more severe crashes.

Based on the standard definitions by the National Safety Council (NSC), the severity levels of crashes and injuries can be classified into the five “KABCO” injury levels, as shown in Table 3.1 (Dixon and Monsere, 2007).

Table 3.1 Crash Severity Level — KABCO Scale

Severity Level	Description
K-Fatal	One or more deaths
A-level injury	Incapacitating injury preventing victim from functioning normally
B-level injury	Non-incapacitating but visible injury
C-level injury	Probable but not visible injury
PDO	Property damage only

Based on this standard scale, safety researchers have proposed the following methods for crash severity analysis:

- *Equivalent Property-Damage-Only (EPDO) method*: weights fatal and injury crashes against a baseline of property-damage-only crashes.
- *Relative Severity Index (RSI) method*: weights the average "comprehensive cost" of crashes at that severity level.
- *Other methods*: including calculating the ratio of fatal crashes to total crashes or computing the fatal crash rates, fatal plus injury crash rates, and total crash rates for each facility type.

The detailed procedures associated with the first two methods are presented below:

3.4.2.1 Procedures for the EPDO method

The EPDO method gives each of the injury levels (KABC) a prespecified weight, based on the base weight of 1 for property-damage-only crashes.

Basically, three types of severity indexes can be used to determine the hazardousness of the site:

a) EPDO index:

$$EPDO\_Index = w_K K + w_A A + w_B B + w_C C + P \qquad (3\text{-}1)$$

where w_i is the weight for each injury type K, A, B, and C, and K, A, B, C, P are the crash frequencies for each type K, A, B, C, and P, respectively.

b) EPDO severity index:

$$EPDO\_SI = [EPDO\_Index]/T \qquad (3\text{-}2)$$

where T is the total crashes at the location.

c) EPDO rate:

$$EPDO\_Rate = [EPDO\_Index \times 10^6]/[AADT \times days] \qquad (3\text{-}3)$$

where AADT is the Average Annual Daily Traffic for the study period and *days* is the number of days in the study period.

The EPDO method takes into account the factor of crash severity, but it requires more data than the simple method with the crash frequency/density or crash rate. On the other hand, since the weight for each crash injury type can be adjusted in practice, this method can yield somewhat subjective results.

3.4.2.2 Procedures for the RSI method

The RSI method multiplies the crash frequency at each severity level by the average "comprehensive cost" for crashes at that severity level. The subtotals for each of these severity-specific costs are summed, and the sum is divided by the total crash frequency, as shown in the following equation:

$$RSI = (C_K K + C_A A + C_B B + C_C C + C_P P)/(K + A + B + C + P) \qquad (3\text{-}4)$$

The RSI method allows the inclusion of crash severity in screening high-crash locations. However, like the EPDO methods, it also requires more information about each site than the simpler methods. Additionally, the RSI method, through its use of severity cost, introduces estimated measures into the computation rather than utilizing the data as is. If these estimated measures are not accurate, the resulting list of priority locations will be inaccurate.

3.4.3 ***Procedures for Quality Control Methods***

Although all of the above methods generate useable lists for hazardous site ranking, none of them employs any measure of statistical significance. The quality control method, also referred to as the critical ratio method, attempts to maximize the probability that only “truly” hazardous locations will be identified.

A statistical test based on the commonly accepted assumption that traffic crashes are Poisson (randomly) distributed is used to determine whether the actual crash frequency, crash density, or crash rate of a particular location is statistically higher than a predetermined average rate of locations with similar physical characteristics. All methods in this family can be divided into the following two categories:

a) Number Quality Control method

For each roadway category, the critical crash frequency/density is calculated based on the average value, traffic volume, and a Poisson distribution probability constant of a desired level of significance:

$$F_c = F_a + k\sqrt{\frac{F_a}{M}} + \frac{1}{2M} \qquad (3\text{-}5)$$

where F_c is the critical crash frequency/density, F_a is the average crash frequency/density within the same category, k is the level of confidence factor, and M is millions of vehicle miles (for sections) or millions of vehicles (for interchanges).

b) Rate Quality Control method

The procedures of the Rate Quality Control method are very similar to those of the Number Quality Control method. The critical crash rate is calculated using the following equation:

$$R_c = R_a + k\sqrt{\frac{R_a}{M}} + \frac{1}{2M} \tag{3-6}$$

where R_c is the critical crash rate, R_a is the average crash rate within the same category, k is the level of confidence factor, and M is millions of vehicle miles (for sections) or millions of vehicles (for interchanges).

If the actual crash frequency/density/rate of a particular location is higher than the critical crash frequency/density/rate for the corresponding road type, that location is considered to have an unusually high number of crashes and is designated as a high-crash location.

The quality control methods recognize the random nature of traffic crashes and take into account traffic exposure in the analysis process. Also, they allow responsible agencies to determine the priorities by grouping locations according to their functional classification. Though these are improvements over the previous methods, they still have some notable deficiencies.

For instance, compared with the simpler methods, the quality control methods are quite data intensive. Additionally, the assumption that all crashes follow the Poisson distribution has been questioned in the recent literature. The negative binomial distribution, which assumes that the crash counts are usually more widely dispersed than would be consistent with the Poisson assumption, has been adjudged a better representation (Hauer, 2002). Finally, the choice of which k-factor value to pick is highly subjective, giving rise to possible ambiguity in results from year to year.

3.4.4 *Composite Methods*

Three composite methods have been found in the state-of-the-practice procedures: the frequency-rate method, the weighted rank method, and the crash probability index (CPI) method.

3.4.4.1 Procedures for the frequency-rate method

The frequency-rate method combines the crash frequency/crash density method and the crash rate method. This method classifies all candidate sites as high-crash locations if their crash frequency (or crash density) and crash rate exceed the present thresholds. The crash frequency or crash density is used to create the initial list, and the crash rate is used to produce the final list.

Note that some candidate sites with high crash frequencies/densities under this method may appear to be problematic, but they may not be ranked at the hazardous level if the traffic volumes are also high. On the other hand, sites with high crash rates due to extremely low traffic volumes and low crash frequencies/densities may not meet the critical values for classification as priority list locations.

3.4.4.2 Procedures for the weighted rank method

The weighted rank method combines some of the previous methods (such as crash frequency/density, crash rate, and crash severity) in calculating a single index value for each site. Two kinds of composite indexes are often used in the weighted rank method (Pulugurthaa et. al., 2007):

a) *Sum-of-the-rank method*

$$SR(j) = \sum_i w(i,j) \times rank(i,j) \tag{3-7}$$

where i is the selected method (e.g., crash frequency/crash density/crash rate/crash severity); j is the location to be screened; $w(i,j)$ is the weighting factor for selected method i at location j; and $rank(i,j)$ is the ranked order by selected method i at location j.

b) *Crash score method*

$$scoreCI(i,j) = \frac{CI(i,j)}{\max CI(i)} \times 100 \tag{3-8a}$$

$$CS(j) = \sum_i w(i,j) \times scoreCI(i,j) \tag{3-8b}$$

where $CI(i,j)$ is the actual value for selected method i at location j; and $\max CI(i)$ is the maximal value for selected method i among all the locations.

Note that the weights can be adjusted in practice, based on an agency's priorities. As a result, the identification results from this composite index method are flexible and somewhat subjective.

3.4.4.3 Procedures for the crash probability index (CPI) method

The crash probability index (CPI) method, much like the weighted rank method, combines the information from the previous methods. As part of the CPI method, when a site has a significantly worse than average crash frequency/density, crash rate, or severity distribution, it is assigned penalty points. The overall CPI for a site is a summation of the penalty points across these three measures. Its procedure can be summarized as follows:

a) If the crash frequency/density, crash rate, and the casualty ratio do not equal or exceed their corresponding critical values, the CPI for the site is zero.

b) If the crash frequency/density equals or exceeds the corresponding critical crash frequency/density, assign five penalty points.

c) If the crash rate equals or exceeds the corresponding critical crash rate, assign five penalty points.

d) If the casualty ratio equals or exceeds the corresponding critical casualty ratio, assign ten penalty points.

e) Add the sub-CPI penalty points to obtain the site CPI.

It should be mentioned that the CPI method also requires an extensive data set and tremendous computing efforts. Additionally, adjustment of the sub-CPI penalty points can be highly subjective.

3.5 RECOMMENDATIONS

This chapter has reviewed all methods available in the literature for ranking and selection of hazardous locations. Their pros and cons, along with recommendations for enhancing the procedures used in Maryland, are summarized below:

a) *Using safety performance functions (SPFs) and observed crash frequency for reliable estimation of site crash frequency* — As discussed in the previous sections, the combined use of SPF and observed crash frequency could effectively reduce the regression to the mean problem.

b) *Developing and calibrating SPFs for the State of Maryland* — Instead of using the SPFs developed by other states, it is essential that Maryland develop and calibrate its own SPFs to better estimate crash frequency. SPFs should be developed and calibrated for different types of sites and for different severity levels.

c) *Using negative binomial distribution to represent the variation of crash frequency* — To better describe the usually overdispersed crash data, negative binomial distribution, instead of Poisson distribution, should be used in the significance tests in order to obtain a more reliable conclusion.

d) *Allowing sliding windows across the adjacent road section sites* — Instead of using fixed-length sliding windows, the evaluation windows should be allowed to slide across adjacent road section sites (i.e., one portion of the sliding window could be in the previous section while the other is in the next section). Allowing sliding windows to be placed across two different sections could effectively check whether these locations experience abnormally high crash frequencies due to changes of section characteristics that might not be easily checked by considering the two sections separately.

e) *Develop a multi-criteria system to enhance the SHA's current procedures for selection and ranking high-crash locations* — Most existing methods for identifying and ranking high-crash locations are based mainly on crash frequency and rate, which are relatively straightforward but fail to truly reflect the complex interactions between such contributing factors as crash nature, severity level, behavior of driving populations, and geometric features. Thus, a multi-criteria system may be desirable, as it can take into account the state-of-the-practice experience, state-of-the-art knowledge, and currently available crash information.

CHAPTER 4 COST/BENEFIT ANALYSIS

4.1 INTRODUCTION

Ensuring the maximum safety for roadway users entails the design and implementation of remedial measures for all locations identified as hazardous. However, due to resource constraints, most responsible agencies can only implement proposed countermeasures for a limited number of locations each year. Thus, how to effectively compare, select, and prioritize locations for safety improvement has emerged as one of the most critical issues for highway agencies.

To effectively compare countermeasures among all candidate locations, most state highway agencies have employed one of the following indicators for their cost/benefit analysis:

- *Reduction in crash frequency* — which measures the reduction in crashes due to implementation of the proposed countermeasures. Using this indicator ensures that the selected countermeasures can result in the most effective safety improvement, not taking into account the implementation cost.
- *Cost effectiveness* — which reflects the cost of the countermeasure for reducing one crash. Its advantage lies in its flexibility at assessing the trade-off between the implementation cost and the resulting improvement. This indicator, however, fails to account for any reduction to the severity level.
- Cost/*benefit ratio and net benefit* — which considers implementation costs, benefits, and the resulting net benefits. This indicator has the strength of allowing different benefit weights for different levels of crash severity improvement.

Over recent decades, traffic safety researchers have proposed a large body of cost/benefit analysis methods for such a need. The remainder of this chapter will summarize the core concepts of those methods.

4.2 MARYLAND PROCEDURES FOR COST/BENEFIT ANALYSIS

This section reviews the cost/benefit analysis method currently used by the Maryland SHA (MDSHA, 2007a), which includes estimations of future crash frequency, countermeasure effectiveness, and the resulting costs and benefits.

4.2.1 Procedures for estimating the future crash frequency

The Maryland procedure involves estimating the future crash frequency for each type of collision for only the year of countermeasure implementation. The future crash frequency is projected using the following simple equation:

$$FREQ_i^c = RATE_i^c \times VOL_i \tag{4-1}$$

where $FREQ_i^c$ is the crash frequency of collision type *c*; $RATE_i^c$ is the crash rate of collision type *c*; and VOL_i is the traffic volume of the study location in the year of countermeasure implementation. Thus, the estimation of the future crash frequency is based on the estimated crash rate and traffic volume for the future period, where the crash rate in the implementation year, $RATE_i^c$, is assumed to equal the average of the three years before the implementation. In contrast, the estimated volume for the implementation year, VOL_i, is projected with a linear variation based on the traffic volumes for the three years preceding the implementation.

Note that, despite the convenience of using only minimum data, the current approach used in Maryland for estimating future crash frequencies does not consider *the volume-dependent crash rate or the nonlinear nature of traffic volume variation.*

4.2.2 Procedures for estimating countermeasure effectiveness

The current Maryland procedure estimates countermeasure effectiveness in terms of crash reduction, based on the following equation:

$$FreqRed_{im}^c = FREQ_i^c \times FAC_m^c \tag{4-2}$$

where $FreqRed_{im}^c$ is the reduction in crash frequency for collision type *c* in the year of implementation if countermeasure *m* is implemented; $FREQ_i^c$ is the estimated crash frequency of collision type *c* in the year of countermeasure implementation; and FAC_m^c is the crash reduction factor of countermeasure *m* in reducing collision type *c*.

Equation 4-2 allows the computation of the benefit of reducing the frequency for collision type *c* due to the implementation of countermeasure *m*, using the following equation:

$$FYB_{im}^c = FreqRed_{im}^c \times AccCost^c \tag{4-3}$$

where $AccCost^c$ is the average annual collision cost incurred by collision type *c*.

Most of the crash reduction factors used in the above procedure are derived from the California Division of Highways, the Mississippi State Highway Department, and the New York State DOT (MDSHA, 2007a); these factors may not precisely reflect the actual effects of countermeasures for local (Maryland) driving populations.

4.2.3 Procedures for estimating costs and benefits

The current Maryland procedure uses the Equivalent Uniform Annual Cost (EUAC) and Equivalent Uniform Annual Benefit (EUAB), which are commonly adopted in project evaluation, to estimate costs and benefits throughout the evaluation period. The main idea of the EUAC and EUAB is to evenly distribute all incurred costs (EUAC) and gained benefits (EUAB) of the countermeasures, including all necessary discounts, like interest rate, over its entire service life. For the EUAC, the Maryland procedure has included: (i) implementation costs (i.e., all costs incurred to implement the countermeasures); (ii) operation/maintenance costs (i.e., the annual cost incurred to operate/maintain the countermeasure); and (iii) salvage costs (i.e., any monetary value retained after the service life of the countermeasure).

For the EUAB, the Maryland procedure includes only the benefits resulting from the reduction in crashes due to the countermeasure implementation. More specifically, its EUAB is evaluated from: (1) *all FYBs* resulting from implementation of the selected countermeasure, (2) the *interest rate* used to discount the future year benefits to their present value for the evaluation of the EUAB, and (3) the *traffic volume growth rate* used with the FYBs to estimate the future benefit due to crash reduction.

Overall, the above procedures for estimating the EUAC and EUAB are relatively simple and convenient for use by practitioners. However, they have the relatively strong embedded assumption that a direct relationship exists between traffic volume and the resulting benefits. Also, the hypothesis that the rate of traffic volume growth will remain constant over the future time horizon may not be consistent with the actual patterns in some regions.

4.2.4 Selected indicators for countermeasure comparison

Maryland’s current procedure employs the cost/benefit ratio, based on the EUAC and EUAB, as the indicator for comparing different countermeasures. A countermeasure will be considered potentially effective provided that its estimated cost/benefit ratio exceeds unity.

4.3 SAFETYANALYST PROCEDURES

This section presents the procedures for cost/benefit analysis adopted by the SafetyAnalyst software (FHWA, 2006), including its estimation of future crash frequency, countermeasure effectiveness, costs and benefits, and selection of indicators for comparison.

4.3.1 *Procedures for estimating the future crash frequency*

SafetyAnalyst estimates the crash frequency for a target year using an empirical Bayesian (EB) approach (see Appendix II). Using this EB-based crash frequency, SafetyAnalyst offers the following equation for predicting the crash frequency of year *n* in the future, $FREQ_{EB}^{n}$:

$$FREQ_{EB}^{n} = \frac{FREQ_{EB(TOT)}}{FREQ_{SPF(TOT)}} FREQ_{SPF}^{n} \tag{4-4}$$

where $FREQ_{EB(TOT)}$ and $FREQ_{SPF(TOT)}$ are, respectively, the total EB- and SPF-based crash frequencies over years in the before period; and $FREQ_{SPF}^{n}$ is the SPF-based crash frequency of year *n* in the future period. This future SPF-based crash frequency is evaluated with the same SPF but uses a constant growth factor to adjust the AADT.

Note that SafetyAnalyst estimates the crash frequencies based not only on the average frequency for the target location but also on the SPFs calibrated with data from similar locations. The main advantage of including SPFs in the estimation is to remove the biases incurred by temporal fluctuations of the crash frequency data.

Equation 4-4 is grounded on the following two assumptions: (1) traffic volume for estimating the SPF-based crash frequency will increase at a constant rate, and (2) the ratio between the EB- and SPF-based crash frequencies will remain unchanged in the future period. These assumptions may not be valid for use in a scenario where the period after countermeasure implementation is relatively long.

4.3.2 Procedures for estimating countermeasure effectiveness

Similar to the procedure adopted in Maryland, the SafetyAnalyst procedure employs a crash modification factor (AMF) in estimating the crash frequency after the implementation of countermeasures. However, with SafetyAnalyst, each crash severity level has its own AMF that may not be a constant. For instance, the AMF for countermeasures such as flattening horizontal curves and widening lanes may vary with the design characteristics. In contrast, the countermeasure of implementing signals at intersections shall have an AMF of constant value, as its impact on safety improvement does not depend on the given signal design.

Based on the selected list of AMFs, SafetyAnalyst defines the benefit of reducing crashes at severity level s in year n due to the implementation of countermeasure m as follows:

$$BENE_m^{ns} = FREQ_{EB}^{n} \times \left(1 - AMF_m^{s}\right) \times AccCost^{s} \tag{4-6}$$

where $AccCost^s$ is the average cost of each crash of severity level s.

With a well-calibrated set of AMF functions, SafetyAnalyst can better estimate the safety improvement produced by the proposed countermeasures, helping responsible agencies to maximize the resulting implementation effectiveness. However, for those combined countermeasures, SafetyAnalyst assumes that their individual benefits are independent rather than interrelated, which may underestimate the actual benefits.

4.3.3 Procedures for estimating cost and benefit over the evaluation period

The SafetyAnalyst software employs the method of present value to represent the cost and benefit of the target countermeasure over the evaluation period. Based on the construction costs of the proposed countermeasure, SafetyAnalyst will perform its present value method with the following two steps: (1) estimating the uniform annual construction cost throughout the service life of the countermeasure, and (ii) computing the present values for the uniform annual construction costs throughout the evaluation period. These two steps could be represented with Equations 4-7 and 4-8:

$$ACC_m = CC_m \times \frac{R\left(1+R\right)^{S_m}}{\left(1+R\right)^{S_m} - 1} \tag{4-7}$$

$$PCC_m = ACC_m \times \frac{\left(1+R\right)^{N} - 1}{R\left(1+R\right)^{N}} \tag{4-8}$$

where CC_m, ACC_m, and PCC_m are, respectively, the construction cost, annual construction cost, and present values of construction costs for countermeasure m; S_m is the service life of countermeasure *m*; *N* is the duration of the evaluation period; and *R* is the annual rate of return.

Compared to the cost estimation procedures used by the Maryland SHA, the method offered by SafetyAnalyst has the following advantages: (1) it uses the present values to give a precise cost estimation of the proposed countermeasures; and (2) it takes into account the countermeasure service life and the evaluation period in the cost estimation. Note that SafetyAnalyst takes only a portion of the construction costs as the cost of the proposed countermeasure. The portion to be used depends on the length of the evaluation period *N* and the service life S_m, of the proposed countermeasure. Also note that its estimation of the present value of the benefits (PB_m), based on the annual benefit ($BENE_m^{ns}$), can be done with the following equation:

$$PB_m = \sum_{s=1}^{S} \sum_{n=1}^{N} \frac{BENE_m^{ns}}{(1+R)^n} \tag{4-10}$$

where *S* is the number of different severity levels considered. This estimated present benefit shares the same advantage discussed in previous sections: it considers the evaluation period and service life of the proposed countermeasures.

4.3.4 Indicators for countermeasure comparison

SafetyAnalyst compares all candidate countermeasures using two different approaches: priority ranking and criteria optimization. In priority ranking, countermeasures will be ranked based on the following indicators: (1) cost effectiveness; (2) EPDO-based cost effectiveness; (3) cost/benefit ratio; (4) net benefits; (5) construction costs; (6) safety benefits; (7) total number of crashes reduced; and (8) number of fatal and injury crashes reduced. All monetary values associated with the costs and benefits for ranking analysis are taken as the present value so that users can then determine the countermeasure for implementation based on the available budget and the ranked list. Some of those indicators are proposed uniquely by SafetyAnalyst. We thus further discuss them below.

The *EPDO-based cost effectiveness* (i.e., the equivalent-property-damage-only-based cost effectiveness) is similar to *cost effectiveness*, except that it takes the total crash reduction as the weighted sum of reduced crashes and their severity levels. Likewise, the *safety benefits* indicator is expected to be more accurate than that of the *number of total crashes reduced*, as the crash reduction is weighted by the cost associated with each severity level. Although using this indicator may improve estimation accuracy, the extent of improvement depends heavily on the cost adopted for each level of crash severity. The indicator of *construction cost* is not suitable for ranking and selecting countermeasures, since no measurement of benefits (e.g., crashes reduced) is involved in the computation.

4.3.5 Procedures to maximize safety benefits under a budgetary constraint

Instead of choosing the countermeasures with the highest net benefits (or any other evaluation indicator), SafetyAnalyst offers the following optimization approach to consider the trade-offs between the costs and benefits of the countermeasures so that the selected improvement schemes will maximize the total net benefit under any given budget:

$$Maximize \qquad TB = \sum_{l} \sum_{m} NB_{lm} Z_{lm} \tag{4-10a}$$

$$Subjected.to \quad \sum_{m} Z_{lm} = 1 \quad \forall l \tag{4-10b}$$

$$\sum_{l} \sum_{m} PC_{lm} Z_{lm} \leq B \tag{4-10c}$$

where NB_{lm} is the net benefit of countermeasure m implemented at location l; Z_{lm} is the decision variable of implementation; $Z_{lm} = 1$ if countermeasure m is implemented at location l and equal to 0 if it is not implemented; PC_{lm} is the present value of the implementation cost for implementing countermeasure m at location l; and B is the budget available for safety improvement. Constraint 4-10b limits each location to only one countermeasure, while constraint 4-10c ensures that the total implementation cost of the chosen countermeasure is within the available budget.

One potential improvement for the above optimization approach would be to employ multiple criteria — since multiple criteria are often needed in the selection and evaluation process — and take into account their relative importance.

4.4 PROCEDURES USED BY THE STATE OF INDIANA

Several cost/benefit analyses from different states have been reviewed and compared in the literature (Tarko and Kanodia, 2003). This section will focus on analyzing and commenting on the cost/benefit analysis from Indiana, one of the most comprehensive methods.

4.4.1 Procedures for estimating the future crash frequency

Similar to the use of SPF functions in SafetyAnalyst, both the observed crash frequency and average crash frequency from similar sites are used in Indiana's procedure for estimating the crash frequency of the target location. Equation 4-11 presents such formulations for computing the crash frequency of the present year, $FREQ_{Ind}$, for any severity:

$$FREQ_{Ind} = \frac{\frac{1}{D} + FREQ_{Obv}^{b}}{\frac{1}{D \times FREQ_{SPF}} + Yrb} \times \left(1 + \frac{R}{100}\right)^{Z \times Y_1} \qquad (4\text{-}11)$$

where $FREQ_{Obv}^{b}$ is the observed crash frequency of the evaluated location during the before period b; Yrb is the number of years in the before period with data used in estimation; $FREQ_{SPF}$ is the crash frequency estimated from the SPF for similar locations; D is the overdispersion parameter from the calibration of the corresponding SPF; R is the average percentage change of exposure during the before period; Y_1 is the number of years between the midpoint of the before period and the present year; and Z is a calibrated constant.

If the SPF function provides a good fit with the crash frequency of similar sites, which gives a small value of D, the first terms of the numerator and denominator will be dominated, and more weight will be put on the crash frequency estimated by the SPF. Otherwise, the SPF shall yield a large value of D, and the first terms of the numerator and denominator will approach zero. Consequently, the estimated crash frequency will depend heavily on the observed crash frequency of the evaluated location, $FREQ_{Obv}^{b}$. By multiplying an exposure adjustment factor (EAF) by the estimated current crash frequency (Equation 4-10), the Indiana procedure estimates the crash frequency of year n in the future, $FREQ_{Ind}^{n}$, with the following equation:

$$FREQ_{Ind}^{n} = FREQ_{Ind} \times \left(1 + \frac{R}{100}\right)^{Z \times Y_2} \qquad (4\text{-}12)$$

where Y_2 is the years between the present year and year n in the future.

Like the EB approach adopted by SafetyAnalyst, the Indiana procedure uses the observed and SPF crash frequencies to estimate the present crash frequency. Such an approach could significantly reduce the potential estimation errors due to temporal fluctuations of crash frequency at the target location.

Equations 4-12 and 4-13 assume that crash frequencies change annually by a constant rate, $(1+R/100)^{Z}-1$, with a predefined change in exposure, *R*, and in parameter *Z*. This has the advantage of introducing parameter *Z* to incorporate the nonlinear relationship between the changes in crash frequency and in exposure. As the change in exposure, *R*, depends on the traffic volume, which is assumed to be constant, the future crash frequency found by Equation 4-13 may not be accurate if the target location experiences a substantial change in traffic volume during the evaluation period.

4.4.2 Procedures for estimating countermeasure effectiveness

The current Indiana procedure estimates countermeasure effectiveness based on the crash reduction, evaluated from the equation below:

$$Freq\mathrm{Red}_{nm}^{s} = FREQ_{Ind}^{ns} \times FAC_{m}^{s} \tag{4-13}$$

where $Freq\mathrm{Red}_{nm}^{s}$ is the reduced crash frequency of severity level *s* in year *n* after implementing countermeasure *m*; $FREQ_{Ind}^{ns}$ is the crash frequency of severity level *s* of year *n* after countermeasure implementation; FAC_{m}^{s} is the crash reduction factor of countermeasure *m* in reducing crashes of severity level *s*. By multiplying the reduced frequency of crashes with their associated costs by different severity levels, one can estimate the resulting benefits. If a single location has multiple improvements, the Indiana procedures suggest using a multiplication rule (see Equation 4-14 below) to find the overall crash reduction factor on severity level *s*, FAC^{s}.

$$FAC^{s} = 100 - \prod_{m}\left(100 - FAC_{m}^{s}\right) \tag{4-14}$$

The crash reduction factors adopted in the Indiana procedures were derived from three major sources: (1) Indiana’s own data, developed and calibrated by the state; (2) reports from FHWA, and (3) data adopted from other states, such as Missouri, Colorado, Kansas, California, Kentucky, Iowa, Florida, New York, and Kansas.

4.4.3 Procedures for estimating costs and benefits over the evaluation period

The Indiana procedure uses the EUAC and EUAB to estimate the costs and benefits for a proposed countermeasure over the evaluation period. In computing the EUAC, the Indiana procedure includes countermeasure implementation costs, operation/maintenance costs, and salvage costs. For the EUAB, the Indiana procedure suggests first estimating the reduced crash frequency for each year in the future, as discussed in the previous section, and then computing the annual benefit with an inflation-adjusted crash cost, $AccCost^s$, and the following expression:

$$AccCost^s = AccCost_0^s \times \left(1 + \frac{F}{100}\right)^{Y_3} \tag{4-15}$$

where $AccCost_0^s$ is the crash cost for the year when the unit crash cost (Yrc_0) is computed; Y_3 is the number of years between the present year and Yrc_0; and F is the average inflation rate in the Y_3 period.

Note that, unlike Maryland and SafetyAnalyst, Indiana takes the inflation rate into account in the cost/benefit analysis. If the inflation rate modification is neglected, the actual unit crash cost (or benefit) may be either underestimated (if inflation occurs) or overestimated (if deflation occurs).

4.4.4 Selection of indicators for countermeasures comparison

The Indiana procedure uses the cost/benefit ratio, based on the EUAC and EUAB found in the previous section, as the indicator for comparison. Indiana views countermeasures with cost/benefit ratios exceeding unity as economically beneficial for implementation. For those with cost/benefit ratios less than one, the Indiana procedure suggests that users take into account their secondary benefits, including several economic benefits such as improved capacity or reduced junction delay.

Note that, with the addition of secondary benefits, more potentially beneficial countermeasures, which may not be economically beneficial based on crash reduction alone, could be included for the final selection. However, it should be noticed that costs and benefits always come in pairs. One shortcoming of the current Indiana procedures is their failure to consider the secondary costs associated with the proposed countermeasures, which may create adverse impacts to nearby freeway/road systems in spite of their benefits in crash reduction at the target intersection.

4.5 RECOMMENDATIONS

This chapter has reviewed the cost/benefit analysis methods used in the Maryland procedure, SafetyAnalyst, and the Indiana procedure with respect to estimating: future crash frequency, countermeasure effectiveness, the costs and benefits of countermeasures. We also compared the selected indicators. The evaluation results suggest the following recommendations for enhancing the current procedures used in Maryland for cost/benefit analyses:

a) *Adopt nonlinear estimations of future traffic volumes.* As discussed in section 4.2.1, employing nonlinear curves to find the trend of the future volume variation will more precisely estimate future traffic volumes over long periods.

b) *Develop and calibrate crash reduction functions for the Maryland data.* As the currently used crash reduction factors are derived from other states, it is essential for Maryland to produce those functions with its local data. For each countermeasure type, Maryland should develop and calibrate crash reduction functions for different severity levels, ranging from property-damage-only crashes to fatal crashes.

c) *Consider secondary costs/benefits.* As discussed in section 4.4.4, the implementation of countermeasures will reduce not only crash frequency, but also have other impacts on the neighboring freeway/road systems. Thus, it is essential to include secondary costs and benefits in evaluating proposed countermeasures.

d) *Consider using multiple selection indicators.* Different selection indicators, such as those adopted in SafetyAnalyst (section 4.3.4), should also be considered in performing cost/benefit analyses and comparisons of candidate countermeasures, as each of those indicators has its own strengths and deficiencies.

CHAPTER 5 COUNTERMEASURE EVALUATION

5.1 INTRODUCTION

The core of the evaluation task is to compare the crash frequency and severity level of a location after implementing the proposed countermeasures with those of the do-nothing scenario. This differs from the cost/benefit analysis, which is based solely on the predicted future crash frequency; performing the countermeasure evaluation requires both the collected (current condition) and estimated (do-nothing scenario) accident information.

In general, four major issues may determine whether or not an evaluation of the proposed countermeasures is reliable: (1) the estimated crash frequency, crash types, and severity levels at the study location during the evaluation period under the *do-nothing scenario;* (2) the *regression-to-the-mean bias*, which may result in either overestimating or underestimating the efficiency of the countermeasures (crash reduction); (3) the *indicators selected* for comparing different countermeasures; and (*4) significance tests* to confirm that the reduced crashes are, indeed, due to the implemented measures.

The remaining sections of this chapter focus on reviewing the procedures for countermeasure evaluation adopted by Maryland, SafetyAnalyst, and other states. It will also include some recommendations for enhancing the current procedures used by Maryland's SHA in this regard.

5.2 MARYLAND PROCEDURES

This section will illustrate the countermeasure evaluation procedure currently adopted in Maryland (MDSHA, 2001, 2002, 2006, 2007a, 2007b and 2007c) with respect to the aforementioned four critical issues.

5.2.1 Do-nothing estimation

The purpose of the do-nothing estimation is to approximate the crash frequency/rate at the target location if the countermeasure was not implemented. The estimated results serve as the basis for finding the percentage change in the crash frequency/rate before and after the implementation.

The Maryland procedure takes the crash rate for comparison so that the impact of traffic volume on crash frequency can be removed. Similar to the estimation of future crash frequency in the cost/benefit analysis, Maryland recommends taking this estimated rate directly as the average of crash rates over the three years before the implementation. To improve the accuracy of this estimation, Maryland procedures require estimating the crash rates for different types of collision, such as rear-end or left-turn collisions, and different severity levels, such as fatal or property-damage-only crashes.

The strength of Maryland's methodology for do-nothing estimation lies in using different crash rates for different types of collision and severity levels. Doing so allows a better determination of whether the implemented countermeasure has reduced the crash rate of the expected types of crash and a better assessment of whether the implemented countermeasure has introduced any unexpected safety issues, such as increasing the crash rate of any other crash types.

Like the procedures discussed in section 4.2, the current procedures for do-nothing estimation have the major shortcoming of using a constant crash rate, which may not be consistent with the nature of accidents. Besides, the consideration of only a single injury level in the evaluation (MDSHA, 2001, 2002 and 2007c) should be enhanced to improve the reliability of the estimation of effectiveness.

5.2.2 Regression-to-the-mean bias

As discussed in Appendix I, the regression-to-the-mean problem is mainly caused by using the data from a short "before" period to compute the estimated crash frequency in the "after" period. The countermeasure evaluations completed in Maryland over the past several years (MDSHA, 2001, 2002 and 2007c) used the average of data from three before years as the do-nothing frequency in the after period; thus, its results may suffer from the regression-to-the-mean bias.

5.2.3 Indicators for measuring effectiveness

The current procedure in Maryland suggests using cost effectiveness, cost/benefit ratio, and change in crash frequency as the set of indicators for evaluating the effectiveness of the implemented countermeasures. The EUAC (identical to that discussed in section 4.2.3, except using the actual implementation cost) and EUAB (from the do-nothing crash frequency and the observed crash frequency during the service life of an implemented measure) are taken as the cost and benefit for computing these indicators.

Note that both the cost effectiveness and cost/benefit ratio are aggregated measures of effectiveness; they combine the effect of countermeasures for all collision types into a single indicator to facilitate the comparison. In contrast, the Maryland procedure recommends computing the change in crash frequency separately for each collision type, which is expected to better measure the pros and cons of each implemented countermeasure.

5.2.4 Significance tests

As discussed in Section 5.1, significance tests determine whether the reduction in crash frequency actually results from implementing the countermeasure rather than from random variation. Maryland's current procedure assumes that all crashes follow a Poisson distribution; the significance of a reduction is determined with the standard figures shown in Figure 5.2.

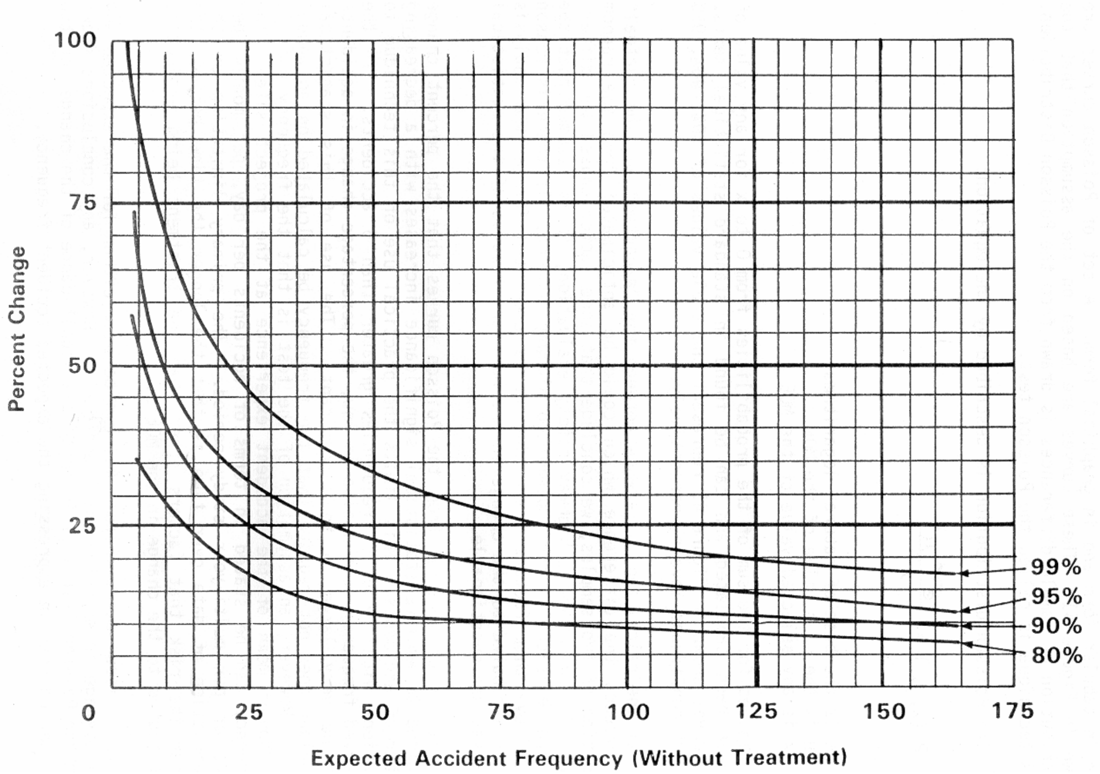

Figure 5.1 Crash reduction statistical confidence intervals
(Source: MDSHA, 2007c)

The Maryland procedure takes the do-nothing crash frequency — i.e., the expected accident frequency in Figure 5.2 — as the mean of the Poisson distribution used to represent the variation of crash frequency. The curves in Figure 5.2 represent the relationship between the do-nothing crash frequency (the expected frequency) and the percentage change that yields the corresponding confidence level (e.g., 95%) of a candidate countermeasure. Therefore, by considering the do-nothing crash frequency and the percentage change for each type of collision, the significance of a selected countermeasure in reducing the crash frequency of that collision type can be found from Figure 5.2. Note that Poisson distribution has the distinguishing property that its mean is equal to its variance, which makes it unsuited for use at locations with an overdispersed distribution of crash data.

5.3 PROCEDURES USED IN SAFETYANALYST

Following the same review format, this section will describe the countermeasure evaluation procedure adopted in SafetyAnalyst software (FHWA, 2006) with respect to the aforementioned critical issues.

5.3.1 Do-nothing estimation

In SafetyAnalyst, the crash frequency is estimated with the empirical Bayesian (EB) approach described in section 4.3.1. Adopting the EB approach requires the estimation of the SPF-based crash frequency for year *n* in the after period ($FREQ^{n}_{SPF(After)}$) with the corresponding AADT of that year and the SPF for that location. Using the SPF-based crash frequency in the after period and the EB- and SPF-based crash frequency in the before period, Equation 5-1 can estimate the total crash frequency for the do-nothing scenario in the after period ($FREQ_{EB(After)}$):

$$FREQ_{EB(After)} = FREQ_{EB(Before)} \frac{FREQ_{SPF(After)}}{FREQ_{SPF(Before)}} \qquad (5\text{-}1)$$

where $FREQ_{EB(Before)}$ is the total EB-based crash frequency of the location in the before period, which can be estimated with Equation II-1 (see Appendix II); and $FREQ_{SPF(Before)}$ and $FREQ_{SPF(After)}$ are, respectively, the total SPF-based crash frequencies of the location in the before and after periods.

Note that Equation 5-1 uses the same EB- to SPF-based crash frequency ratio from the before period to the after period, which may yield estimation biases like those discussed in Chapter 4.

5.3.2 Regression-to-the-mean bias

To minimize this type of bias in assessing effectiveness, SafetyAnalyst adopts the EB approach to estimate the crash frequency during the before and after periods. The proposed EB approach has the following unique features: (1) *combining the SPF-based crash frequency and the observed crash frequency* in the estimation, which yields a relatively stable estimate, and (2) *efficiently selecting the weights* for the SPF-based and observed crash frequencies. For instance, if the overdispersion parameter computed from the data is small, this method will place a large weight on the SPF-estimated crash frequency, minimizing the effect of temporal fluctuation on the observed crash frequency.

5.3.3 Measurement indicators

In SafetyAnalyst, the percentage change in crash frequency for different severity levels or collision types is used as the major indicator for evaluating the effectiveness of countermeasures. The following equation can be used to estimate the percentage change in severity level *s* ($CHANGE_s$):

$$CHANGE_s = \frac{FREQ^s_{Obv(After)} - FREQ^s_{EB(After)}}{FREQ^s_{EB(After)}} \times 100 \tag{5-2}$$

where $FREQ^s_{EB(After)}$ is the expected EB-based crash frequency of severity level (or collision type) *s* throughout the after period as computed with Equation II-1 (see Appendix II); and $FREQ^s_{Obv(After)}$ is the observed crash frequency of severity level (or collision type) *s* throughout the after period.

By comparing the percentage change in crash frequency with respect to different severity levels (or collision types), one can easily determine whether the implemented countermeasures can effectively yield the expected effectiveness or might cause some other types of safety problems. However, using such an indicator for evaluation has the following two deficiencies: (1) *it does not account for the difference in costs (or benefits) associated with increasing (or reducing) crashes of different severity levels*, and (2) *it neglects the costs associated with the implemented countermeasures*. The diminishing resources for safety improvements make it essential to remedy such deficiencies in the evaluation and selection process.

5.3.4 Significance test

The SafetyAnalyst significance test with respect to the change in crash frequency is accomplished by employing the following index (SIG_s):

$$SIG_s = Abs\left(\frac{CHANGE_s}{SD(CHANGE_s)}\right) \tag{5-3}$$

where $CHANGE_s$ is the percentage change in crash frequency for severity level *s* described in Equation 5-2; and $SD(CHANGE_s)$ is the standard deviation of $CHANGE_s$. SafetyAnalyst suggests that if $SIG_s < 1.7$, one can conclude that the countermeasure has no effect in changing the crash frequency at the 90 percent confidence level. On the other hand, the countermeasures can be viewed as effective in reducing the crash frequency at the 90 percent (or 95 percent) confidence level if $SIG_s \geq 1.7$ (or $SIG_s \geq 2.0$)

The confidence level, which measures the significance of the change in crash frequency, decreases with the value of SIG_s. When the absolute value of $CHANGE_s$ decreases to a very low level, then the observed crash frequency in the after period will be close to that of the do-nothing scenario (Equation 5-1), which thus gives a low significance to the change in crash frequency.

In general, an increase in $SD(CHANGE_s)$ implies that the variation of percentage change in crash frequency is widely spread out. Hence, a large value of $SD(CHANGE_s)$ will offset a large percentage change ($CHANGE_s$) and yield a low significance to the change in crash frequency. On the other hand, a large $CHANGE_s$ along with a small $SD(CHANGE_s)$ indicates a high significance to the change in crash frequency, as it represents a scenario which has a large crash reduction and with a high level of certainty (i.e., small variance).

Note that for $SD(CHANGE_s)$ within a reasonable range, Equation 5-3 gives a reliable estimate of statistical significance to the change in crash frequency. However, for a very small $SD(CHANGE_s)$, the quotient in the equation will become very large and the changes in crash frequency will be considered as significant even with only a small percentage change ($CHANGE_s$). Thus, one should not rely solely on this index in determining the significance of a crash frequency change.

5.4 PROCEDURES BY OTHER STATES

As before, our review of the practices by other state highway agencies will describe only the methods used by Indiana State, which offers by far the most comprehensive and rigorous evaluation program.

5.4.1 Do-nothing estimation

Using an approach similar to the one discussed in section 4.4.1, Indiana State employs the following equation to estimate the crash frequency under the do-nothing scenario, $FREQ_{Ind}^{0}$:

$$FREQ_{Ind}^{0} = \frac{\frac{1}{D} + FREQ_{Obv}^{b}}{\frac{1}{D \times FREQ_{SPF}} + Yrb} \times \left(\frac{E_A}{E_B} \right)^{Z} \tag{5-6}$$

where $FREQ_{Obv}^{b}$, $FREQ_{SPF}$, D, Yrb, and Z have the same definitions as in previous sections. E_A and E_B are, respectively, the average daily exposures during the before and after periods of the countermeasure implementation. The computation of these exposures is based on the AADT entering the target intersection or roadway segment.

The major assumption underlying Equation 5-6 is that the crash frequency, which includes the crash frequency for the present and the do-nothing scenarios, is directly proportional to the exposure-related factor $(E_A)^Z$ only. Thus, the accuracy of the estimated crash frequency for the do-nothing scenario could only be ensured with an updated and well-calibrated parameter Z, which governs the nonlinear relationship between the exposure (AADT) and the crash frequency.

5.4.2 Regression-to-the-mean problem

To minimize the effect of the regression-to-the-mean bias on countermeasure evaluation, Indiana has developed a special method based on the observed crash frequency of the target location and the crash frequency from the SPF of similar locations. Equation 4-12 is set up so that if the SPF is more reliable (i.e., a smaller *D*), the estimation will put more weight on the SPF-estimated crash frequency. Where the SPF is less reliable (i.e., a large D), the estimation will put more weight on the observed crash frequency of the evaluated location. Since the method shares similar statistical properties to the EB-based estimation by

SafetyAnalyst, it is reasonably effective in reducing the regression-to-the-mean estimation bias.

5.4.3 Measuring indicators

The procedures adopted by Indiana suggest using the cost/benefit ratio as the measurement indicator for countermeasure evaluation. This ratio is computed like the EUAC and EUAB, discussed in previous sections, but using actual rather than estimated values. For instance, in computing the EUAB, the Indiana procedures recommend using the do-nothing estimation results and the observed crash frequency after implementation to compute the corresponding benefits. Note that the cost/benefit ratio is commonly used for project evaluation; section 4.1 discusses its strengths and deficiencies.

The cost/benefit ratio used in the Indiana procedure, an aggregated measure of effectiveness, represents the overall effect of the countermeasure on reducing crashes of different severity levels. Although it allows a direct comparison of the effectiveness of different countermeasures, it is difficult for the responsible agencies to tell whether the implemented countermeasure has any adverse effect on any particular crash severity level or collision type.

5.4.4 Significance tests

The significance test adopted by the Indiana procedures is the same as Maryland’s, except that it uses a negative binomial (instead of Poisson) distribution in describing crash frequencies. Note that a negative binomial distribution is generally suited for representing overdispersed crash data that having a mean value differs significantly from the variance. Depending on the spatial pattern of crash data, using such a distribution for statistical test may or may not yield better results than the Poisson assumption.

5.5 RECOMMENDATIONS

The above review results suggest the following enhancements to the procedures currently used by the Maryland SHA:

a) *Using SPFs and observed crash frequency for reliable estimation of site-specific crash frequency* — Combining the use of SPFs and observed crash frequency may yield a more reliable estimate of crash frequency for countermeasure evaluation.

b) *Exploring the use of negative binomial distribution in the significance test* — This would ensure that some overdispersed crash data can be fitted with a proper distribution.

c) *Using SPFs of the after period in estimating the do-nothing crash frequency* — Using an approach similar to SafetyAnalyst would reduce the regression-to-the-mean problem on do-nothing estimations.

d) *Including both aggregated and disaggregated evaluation indicators* — This would enhance the evaluation quality and reliability with all available data, including both the aggregated (i.e., cost/benefit ratio, cost effectiveness, and net benefit) and disaggregated (i.e., percentage change in crash frequency for different severity levels) indicators.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY OF RESEARCH FINDINGS

This study offers a comprehensive review of the safety improvement programs adopted by Maryland, FHWA (SafetyAnalyst), and other state agencies, focusing mainly on the following imperative issues: (1) screening and ranking high-crash locations, (2) prioritizing cost-effective projects for safety improvement; and (3) conducting before/after studies for project implementation plans.

Based on the results of this review, we recommend that the following enhancements be incorporated into the existing safety improvement program in Maryland:

- *Develop a multi-criteria method to enhance the current procedures used by the Maryland SHA to select and rank high-crash locations*: Most existing methods for identifying and ranking high-crash locations are based mainly on either the crash frequency or rate, which are relatively straightforward but fail to truly reflect the complex interactions between contributing factors such as the crash nature, the severity level, the behavior of driving populations, and geometric features. Thus, it is essential that a multicriteria evaluation system be adopted to incorporate the state-of-practice experience and state-of-art knowledge from various available sources.

- *Using SPFs and the observed crash frequency to reliably estimate the site-specific crash frequency*: The combined use of SPFs and the observed crash frequency could effectively reduce the regression-to-the-mean bias at all levels of estimation. Further studies should be carried out to determine whether Maryland should develop its own approach or just follow the EB-based approach suggested by SafetyAnalyst.

- *Developing and calibrating SPFs for Maryland*: Instead of using the SPFs developed by other states, Maryland should develop and calibrate its own SPFs to improve estimations of crash frequency.

- *Using negative binomial distribution to represent the variation of crash frequency:* Due to the mostly overdispersed crash data, Maryland should explore the use of the negative binomial distribution, instead of Poisson distribution, in significance tests of countermeasure effectiveness.

- *Allowing sliding windows across adjacent road section sites:* Instead of using a fixed-length sliding window to identify hazardous locations, Maryland should allow evaluation windows to slide across adjacent road section sites, which would effectively check whether the target locations experience abnormally high crash frequencies due to changes of geometric characteristics.

- *Employing nonlinear estimation for future traffic volume:* As traffic volume does often not increase at a constant rate, it is essential to use a nonlinear model to project its evolution trend with historical data.

- *Developing and calibrating the crash reduction functions with local data*: The set of crash reduction factors currently used in Maryland come from other states; these functions may not precisely reflect the change in crash frequency after countermeasure implementation. To be effective, Maryland should calibrate a crash reduction function for each crash type and severity level, ranging from property-damage-only to fatal crashes.

- *Including secondary costs/benefits in the evaluation*: As discussed in section 4.4, the implementation of countermeasures may not only reduce crash frequency, but also result in other impacts on the entire freeway/road system. This makes it essential to include all such secondary benefits or costs in the process of ranking and selection projects.

- *Applying a benefit-maximizing selection approach*: Because the available budget for safety improvements is always limited, Maryland should explore the trade-offs between costs and benefits among candidate countermeasures, selecting the set that can maximize the overall benefit.

- *Exploring the use of different selection indicators*: Maryland should also explore different selection indicators, such as those adopted in SafetyAnalyst (section 4.3.4), to ensure that all hazardous locations can be effectively identified and that the most effective countermeasures can be implemented.

- *Using SPFs of the after period in estimating do-nothing crash frequency*: To minimize the regression-to-the-mean bias, Maryland’s procedure for estimating the crash frequency for the do-nothing scenario should follow the approach in SafetyAnalyst.

6.2 CONCLUSION

Over the past two decades, both FHWA and state agencies have jointly devoted tremendous resources in developing a comprehensive safety improvement program that has been incorporated into the SafetyAnalyst software. SafetyAnalyst includes both a methodology to guide users in identifying hazardous locations and a set of computerized tools to facilitate project implementation. Much valuable data and many lessons are also available from the SafetyAnalyst documentation, which may offer some effective suggestions for the Maryland SHA to enhance its current safety program, as well as some of its analysis procedures. Hence, it is imperative for responsible staff in the Maryland SHA to take full advantage of all information and tools available in SafetyAnalyst and to upgrade its existing procedures under the available resources and data constraints.

REFERENCES

1. Dixon, K. and Monsere C., 2007. *Evaluating the Effectiveness of the Safety Investment Program (SIP) Policies for Oregon-Literature Review*. Technical Report.
2. Federal Highway Administration (FHWA), 2008. http://safety.fhwa.dot.gov/hsip/fivepercent/, accessed March 15, 2008.
3. Federal Highway Administration (FHWA), 2006. *SafetyAnalyst User's Manual*.
4. Hauer E., 2007. Detection of Safety Deterioration in a Series of Accident Counts *Transportation Research Record* 1542, pp. 38-43.
5. Hauer, E., Harwood, D. W., Council, F. M., and Griffith M. S., 2002. Estimating Safety by the Empirical Bayesian Method: A Tutorial. *Transportation Research Record* 1784, pp. 126-131.
6. Maryland State Highway Administration (MDSHA), 2001. *Continuous Shoulder Rumble Strips (CSRS) on Maryland Highways.* Technical Report.
7. Maryland State Highway Administration (MDSHA), 2002. *Evaluation Maryland's Accident Experience at Location having Red Light Running Detection Cameras.* Technical Report.
8. Maryland State Highway Administration (MDSHA), 2006. *PTSWF Warning Sign Study: Before & After Study Overview and Results.* Technical Report.
9. Maryland State Highway Administration (MDSHA), 2007a. *Maryland's Highway Safety Improvement Program: Annual Report Fiscal Year 2007*. Technical Report.
10. Maryland State Highway Administration (MDSHA), 2007b. *Safety Evaluation of Red-Light Cameras in Maryland.* Technical Report.
11. Maryland State Highway Administration (MDSHA), 2007c. *Maryland's Roundabouts: Accident Experience and Economic Evaluation.* Technical Report.
12. Midwest Research Institute (MRI), 2002. *SafetyAnalyst: Software Tools for Safety Management of Specific Highway Sites (White Paper for Module 1—Network Screening).* Technical Report.

13. Pawlovich, M. D., 2007. *Safety Improvement Candidate Location (SICL) Methods*. Technical Report.

14. Pulugurthaa S. S., Krishnakumarb V. K., and Nambisanc. S. S, 2007. New methods to identify and rank high pedestrian crash zones: An illustration. Accident Analysis *& Prevention*. 39(4), pp. 800-811

15. Robert K. Seyfried, 2008. *Introduction to Crash Analysis.* ITE Training Course.

16. Tarko, A.P. and Kanodia, M., 2003. Hazard Elimination Program – Manual on Improving Safety of Indiana Road Intersections and Sections (FHWA/IN/JTRP-2003/19). Technical Report.

17. United States Government Accountability Office (GAO), 2008. *Highway Safety Improvement Program: Further Efforts Needed to Address Data Limitations and Better Align Funding with States' Top Safety Priorities.* Technical Report.

APPENDIX- I: THE REGRESSION-TO-THE-MEAN PROBLEM

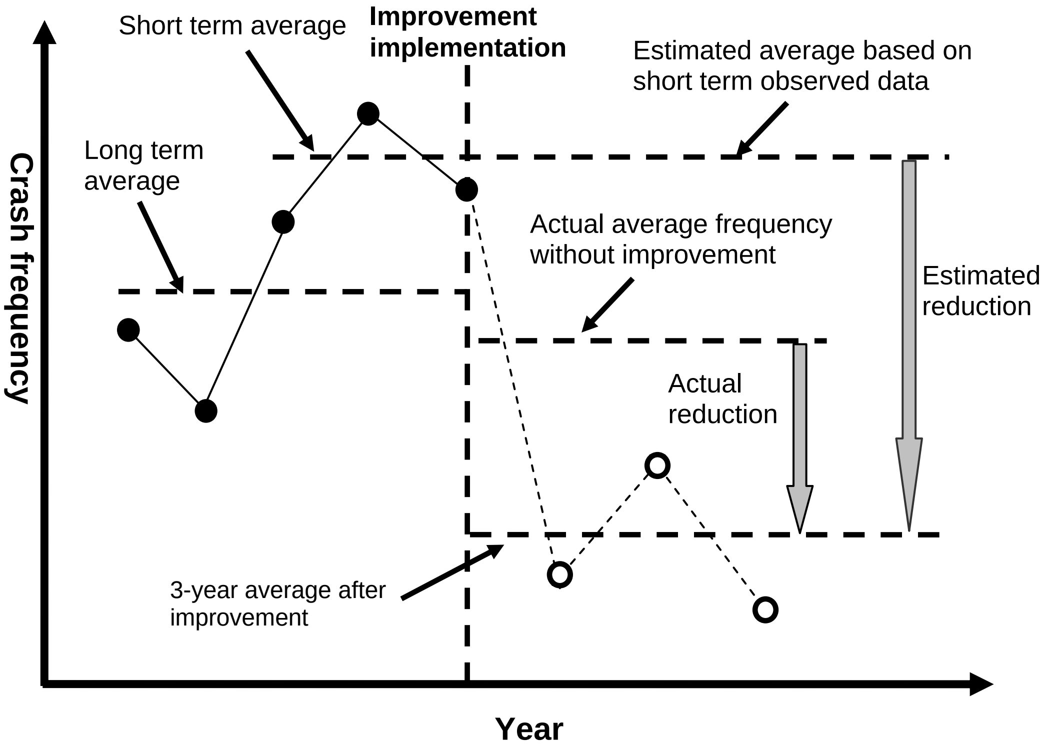

Figure I.1 Regression-to-the-mean

In Figure I.1, the vertical dotted line represents the time during which the countermeasure is implemented. The left of this dotted line shows the variation of crash frequencies at this location before implementation of the countermeasure. Due to the availability of data, most screening methods can only use the short-term average to identify high-crash locations. On the right of the vertical dotted line shows the variation of crash frequencies after countermeasure implementation. The three horizontal lines on the right side respectively (from the top) represent the average crash frequency estimated from the previous short-term average, actual average crash frequency without improvement, and the average crash frequency after the improvement.

Note that the actual average crash frequency without improvement is assumed to be known in this figure for convenience of illustrating the nature of the regression-to-the-mean problem. Comparing to the short-term average before the countermeasure implementation, the average crash frequency without improvement should fall back to a level close to the long-term average. This is due to the fact that such a high crash frequency before the improvement is only a short-term fluctuation, and the crash frequency (given that all other parameters, such as traffic volumes, remain unchanged) will finally “regress” back to the long-term average. If the crash frequency for the do-nothing scenario is estimated solely on the short-term average, the estimated reduction will be larger than the actual number, and thus result in overestimate of the effectiveness of the countermeasures. Some locations experiencing short-term low crash frequencies (compared to their long term averages) will also have the same regression-to-the-mean problem, which would be an underestimate of their countermeasure effectiveness.

APPENDIX- II: THE EMPIRICAL BAYESIAN (EB) APPROACH

The EB-based crash frequency is presented below to clarify the explanations and comments made in this report:

$$FREQ_{EB}^{ls} = w \times FREQ_{SPF}^{ls} + \left(1 - w\right) \times FREQ_{Obv}^{ls} \qquad \text{(II-1)}$$

where, $FREQ_{EB}^{ls}$, $FREQ_{SPF}^{ls}$ and $FREQ_{Obv}^{ls}$ are respectively the EB-based, SPF-based and observed crash frequencies for severity level *s* at location *l*; *w* is the weight of SPF-based crash frequency for estimating the EB-based crash frequency. The EB approach uses two different pieces of crash information (shown in Figure II.1): (1) crash frequencies of locations that are similar to the study location (first term in the right-hand side of equation II-1) and; 2) observed crash frequency of the study location (second term in the right-hand side of equation II-1), for making an accurate estimation of the crash frequency.

The EB approach can achieve an accurate estimation by choosing the proper weight *w* in equation II-1. SafetyAnalyst defines the weight *w* with the following equation:

$$w = \frac{1}{1 + d \times FREQ_{SPF(Before)}^{l}} \qquad \text{(II-2)}$$

where $FREQ_{SPF(Before)}^{l}$ is the sum of the SFP-based crash frequencies for location *l* throughout the before period; *d* is a measure of dispersion for the crash frequencies of the locations used for calibrating the SPF. If locations with a dispersed distribution of crash frequencies are used in the SPF calibration, the parameter *d* will have a large value and thus yield a small weight *w*. Hence, to estimate the EB-based crash frequency with equation II-1, one needs to put more weight on the observed crash frequency of the study location. On the other hand, it is necessary to place more weight on the SPF-based crash frequency to estimate the EB-based crash frequency if the variance of crash frequencies for those locations used in the SPF calibration is small (i.e. a smaller over-dispersion parameter).

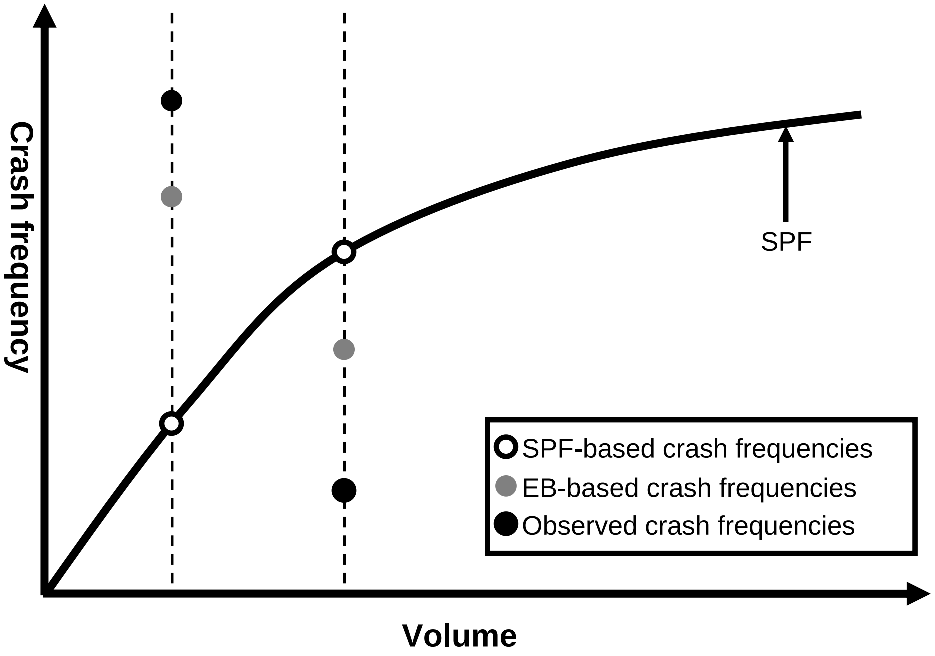

Figure II.1 EB-based, SPF-based and observed crash frequencies