PART A— INTRODUCTION AND FUNDAMENTALS

CHAPTER 3—FUNDAMENTALS

EXHIBITS

CHAPTER 3 FUNDAMENTALS

3.1. CHAPTER INTRODUCTION

This chapter introduces fundamentals for applying the HSM.

The purpose of this chapter is to introduce the fundamental concepts for understanding the roadway safety management techniques and crash estimation methods presented in subsequent chapters of the Highway Safety Manual (HSM).

In the HSM, crash frequency is the fundamental basis for safety analysis, selection of sites for treatment and evaluation of the effects of treatments. The overall aim of the HSM is to reduce crashes and crash severities through the comparison and evaluation of alternative treatments and design of roadways. A commensurate objective is to use limited safety funds in a cost effective manner.

This chapter presents the following concepts:

- An overview of the basic concepts relating to crash analysis, including definitions of key crash analysis terms, the difference between subjective and objective safety, factors that contribute to crashes and strategies to reduce crashes;
- Data for crash estimation and its limitations;
- A historical perspective of the evolution of crash estimation methods and the limitations their methods;
- An overview of the predictive method (*Part C*) and AMFs (*Parts C* and *D*);
- Application of the HSM; and
- The types of evaluation methods for determining the effectiveness of treatment types (*Part B*).

Users benefit by familiarizing themselves with the material in Chapter 3 in order to apply the HSM and understanding that engineering judgment is necessary to determine if and when the HSM procedures are appropriate.

3.2. CRASHES AS THE BASIS OF SAFETY ANALYSIS

Crash frequency is used as a fundamental indicator of “safety” in the evaluation and estimation methods presented in the HSM. Where the term “safety” is used in the HSM, it refers to the crash frequency and/or crash severity and collision type for a specific time period, a given location, and a given set of geometric and operational conditions.

Crash frequency is a fundamental quantitative performance measure in the HSM.

This section provides an overview of fundamental concepts relating to crashes and their use in the HSM:

- The difference between objective safety and subjective safety;
- The definition of a crash and other crash related terms;
- Crashes are rare and random events;
- Contributing factors influence crashes and can be addressed by a number of strategies;

- The HSM focuses on reducing crashes by changing the roadway/environment.

3.2.1. Objective and Subjective Safety

Section 3.2.1 presents objective and subjective safety concepts. The HSM focuses on objective safety.

The HSM focuses on how to estimate and evaluate the crash frequency and crash severity for a particular roadway network, facility or site, in a given period, and hence the focus is on "objective" safety. Objective safety refers to use of a quantitative measure which is independent of the observer. Crash frequency and severity are defined in Section 3.2.2.

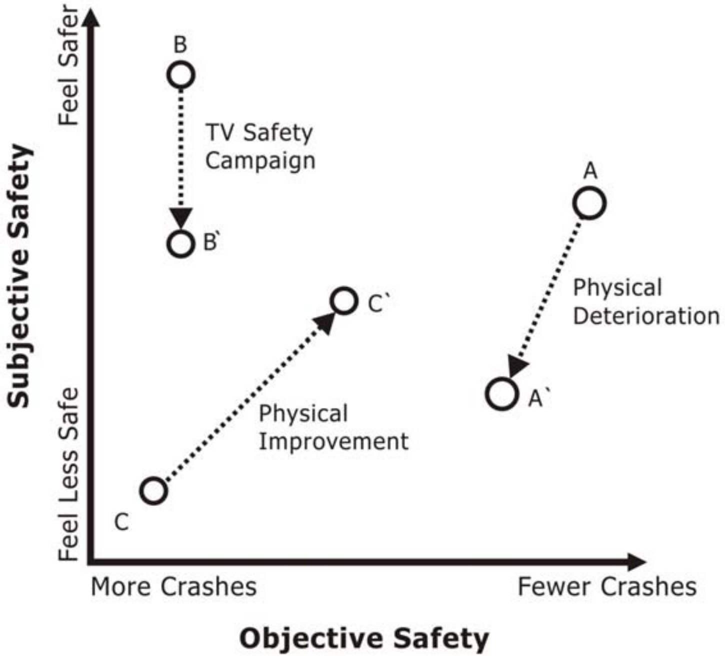
In contrast, "subjective" safety concerns the perception of how safe a person feels on the transportation system. Assessment of subjective safety for the same site will vary between observers.

The traveling public, the transportation professional and the statisticians may all have diverse but valid opinions about whether a site is "safe" or "unsafe." Highway agencies draw information from each of these groups in determining policies and procedures which it will use to affect a change in crash frequency and/or severity among the road or highway system.

Exhibit 3-1 illustrates the difference between objective and subjective safety. Moving to the right on the horizontal axis of the graph conceptually shows an increase in objective safety (reduction in crashes). Moving up on the vertical axis conceptually shows an increase in subjective safety (i.e., increased perception of safety). In this exhibit, three examples illustrate the difference:

- The change between Points A to A′ represents a clear-cut deterioration in both objective and subjective safety. For example, removing lighting from an intersection may increase crashes and decrease the driver's perception of safety (at night).
- The change between Points B to B′ represents a reduction in the perception of safety on a transportation network, For example, as a result of a television campaign against aggressive driving, citizens may feel less secure on the roadways because of greater awareness of aggressive drivers. If the campaign is not effective in reducing crashes caused by aggressive driving, the decline in perceived safety occurs with no change in the number of crashes.
- The change from Point C to C′ represents a physical improvement to the roadway (such as the addition of left-turn lanes) that results in both a reduction in crashes and an increase in the subjective safety.

Exhibit 3-1: Changes in Objective and Subjective Safety



Source: NCHRP 17-27

3.2.2. Fundamental Definitions of Terms in the HSM

Definition of a Crash

In the HSM, a crash is defined as a set of events that result in injury or property damage, due to the collision of at least one motorized vehicle and may involve collision with another motorized vehicle, a bicyclist, a pedestrian or an object. The terms used in the HSM do not include crashes between cyclists and pedestrians, or vehicles on rails.(7) The terms "crash" and "accident" are used interchangeably throughout the HSM.

Definition of Crash Frequency

In the HSM, "crash frequency" is defined as the number of crashes occurring at a particular site, facility or network in a one-year period. Crash frequency is calculated according to Equation 3-1 and is measured in number of crashes per year.

Section 3.2.2 provides fundamental definitions for using

$$Crash\ Frequency = \frac{Number\ of\ Crashes}{Period\ in\ Years} \qquad (3\text{-}1)$$

Definition of Crash Estimation

"Crash estimation" refers to any methodology used to forecast or predict the crash frequency of:

- An existing roadway for existing conditions during a past or future period;

- An existing roadway for alternative conditions during a past or future period;
- A new roadway for given conditions for a future period.

The crash estimation method in *Part C* of the HSM is referred to as the "predictive method" and is used to estimate the "expected average crash frequency", which is defined below.

Definition of Predictive Method

The term "predictive method" refers to the methodology in *Part C* of the HSM that is used to estimate the "expected average crash frequency" of a site, facility or roadway under given geometric design, traffic volumes and for a specific period of time.

Definition of Expected Average Crash Frequency

The term "expected average crash frequency" is used in the HSM to describe the estimate of long-term average crash frequency of a site, facility or network under a given set of geometric design and traffic volumes in a given time period (in years).

As crashes are random events, the observed crash frequencies at a given site naturally fluctuate over time. Therefore, the observed crash frequency over a short period is not a reliable indictor of what average crash frequency is expected under the same conditions over a longer period of time.

If all conditions on a roadway could be controlled (e.g. fixed traffic volume, unchanged geometric design, etc), the long-term average crash frequency could be measured. However because it is rarely possible to achieve these constant conditions, the true long-term average crash frequency is unknown and must be estimated instead.

Definition of Crash Severity

Crashes vary in the level of injury or property damage. The American National Standard ANSI D16.1-1996 defines injury as "bodily harm to a person"(7). The level of injury or property damage due to a crash is referred to in the HSM as "crash severity." While a crash may cause a number of injuries of varying severity, the term crash severity refers to the most severe injury caused by a crash.

Crash severity is often divided into categories according to the KABCO scale, which provides five levels of injury severity. Even if the KABCO scale is used, the definition of an injury may vary between jurisdictions. The five KABCO crash severity levels are:

- K - Fatal injury: an injury that results in death;
- A - Incapacitating injury: any injury, other than a fatal injury, which prevents the injured person from walking, driving or normally continuing the activities the person was capable of performing before the injury occurred;
- B – Non-incapacitating evident injury: any injury, other than a fatal injury or an incapacitating injury, which is evident to observers at the scene of the accident in which the injury occurred;

- C - Possible injury: any injury reported or claimed which is not a fatal injury, incapacitating injury or non-incapacitating evident injury and includes claim of injuries not evident;
- O – No Injury/Property Damage Only (PDO).

While other scales for ranking crash severity exist, the KABCO scale is used in the HSM.

Definition of Crash Evaluation

In the HSM, "crash evaluation" refers to determining the effectiveness of a particular treatment or a treatment program after its implementation. Where the term effectiveness is used in the HSM, it refers to a change in the expected average crash frequency (or severity) for a site or project. Evaluation is based on comparing results obtained from crash estimation. Examples include:

- Evaluating a single application of a treatment to document its effectiveness;
- Evaluating a group of similar projects to document the effectiveness of those projects;
- Evaluating a group of similar projects for the specific purpose of quantifying the effectiveness of a countermeasure;
- Assessing the overall effectiveness of specific projects or countermeasures in comparison to their costs.

Crash evaluation is introduced in Section 3.7 and described in detail in *Chapter 9*.

3.2.3. Crashes Are Rare and Random Events

Crashes are rare and random events. By rare, it is implied that crashes represent only a very small proportion of the total number of events that occur on the transportation system. Random means that crashes occur as a function of a set of events influenced by several factors, which are partly deterministic (they can be controlled) and partly stochastic (random and unpredictable). An event refers to the movement of one or more vehicles and or pedestrians and cyclists on the transportation network.

Crashes are rare – They represent only a very small proportion of the total number of events that occur on the transportation system.

A crash is one possible outcome of a continuum of events on the transportation network during which the probability of a crash occurring may change from low risk to high risk. Crashes represent a very small proportion of the total events that occur on the transportation network. For example, for a crash to occur, two vehicles must arrive at the same point in space at the same time. However, arrival at the same time does not necessarily mean that a crash will occur. The drivers and vehicles have different properties (reaction times, braking efficiencies, visual capabilities, attentiveness, speed choice), which will determine whether or not a crash occurs.

Crashes are random - They occur as a function of a set of events influenced by several factors.

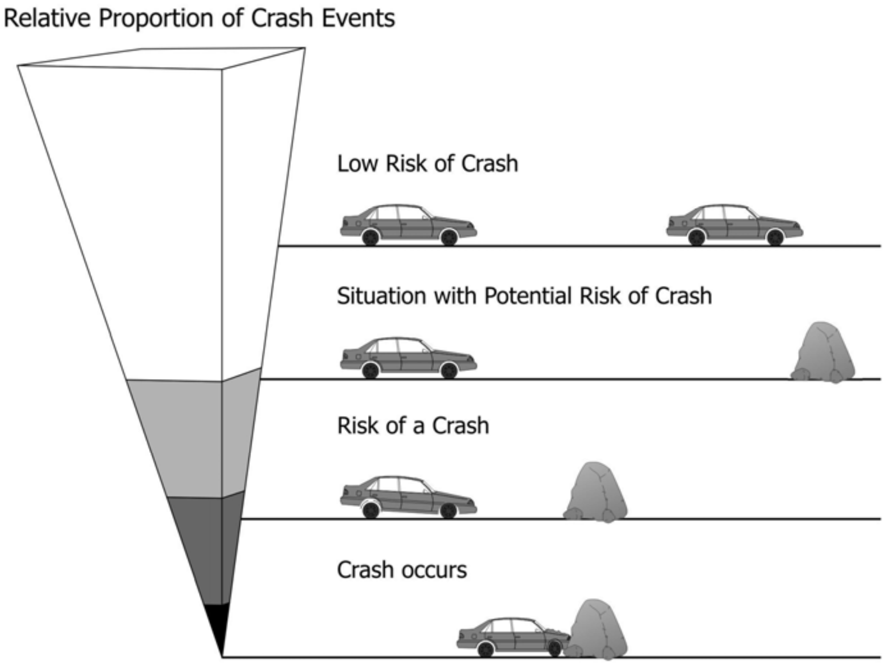
The continuum of events that may lead to crashes and the conceptual proportion of crash events to non-crash events are represented in Exhibit 3-2. For the vast majority of events(i.e. movement of one or more vehicles and or pedestrians and cyclists) in the transportation system, events occur with low risk of a crash (i.e., the probability of a crash occurring is very low for most events on the transportation network).

In a smaller number of events, the potential risk of a crash occurring increases, such as an unexpected change in traffic flow on a freeway, a person crossing a road, or an unexpected object is observed on the roadway. In the majority of these situations, the potential for a crash is avoided by a driver's advance action, such as slowing down, changing lanes, or sounding a horn.

In even fewer events, the risk of a crash occurring increases even more. For instance, if a driver is momentarily not paying attention, the probability of a crash occurring increases. However, the accident could still be avoided, for example by coming to an emergency stop. Finally, in only a very few events, a crash occurs. For instance, in the previous example, the driver may have not applied the brakes in time to avoid a collision.

Circumstances that lead to a crash in one event will not necessary lead to a crash in a similar event. This reflects the randomness that is inherent in crashes.

Exhibit 3-2: Crashes are Rare and Random Events



3.2.4. Crash Contributing Factors

Section 3.2.4 introduces crash contributing factors.

While it is common to refer to the "cause" of a crash, in reality, most crashes cannot be related to a singular causal event. Instead, crashes are the result of a convergence of a series of events that are influenced by a number of contributing factors (time of day, driver attentiveness, speed, vehicle condition, road design etc). These contributing factors influence the sequence of events (described above) before, during and after a crash.

- **Before-crash events** - reveal factors that contributed to the risk of a crash occurring, and how the crash may have been prevented. For example whether the brakes of one or both of the vehicles involved were worn;

- **During-crash events** – reveal factors that contributed to the crash severity and how engineering solutions or technological changes could reduce crash severity For example whether a car has airbags and if the airbag deployed correctly;

- **After-crash events** – reveal factors influencing the outcome of the crash and how damage and injury may have been reduced by improvements in emergency response and medical treatment For example the time and quality of emergency response to a crash.

Crashes have the following three general categories of contributing factors:

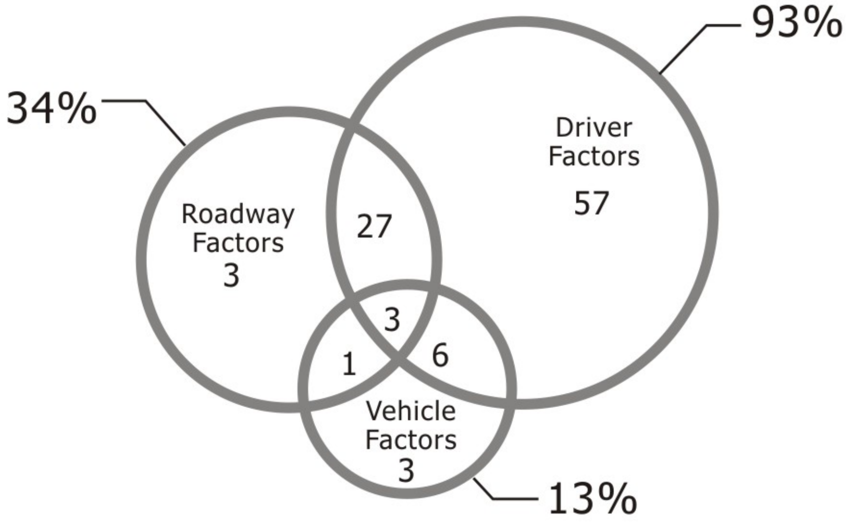
- **Human –** including age, judgment, driver skill, attention, fatigue, experience and sobriety;

- **Vehicle –** including design, manufacture and maintenance;

- **Roadway/Environment** – including geometric alignment, cross-section, traffic control devices, surface friction, grade, signage, weather, visibility.

By understanding these factors and how they might influence the sequence of events, crashes and crash severities can be reduced by implementing specific measures to target specific contributing factors. The relative contribution of these factors to crashes can assist with determining how to best allocate resources to reduce crashes. Research by Treat into the relative proportion of contributing factors is summarized in Exhibit 3-3(10). The research was conducted in 1980 and therefore, the relative proportions are more informative than the actual values shown.

Exhibit 3-3: Contributing Factors to Vehicle Crashes



Source: Treat 1979

A framework for relating the series of events in a crash to the categories of crash contributing factors is the Haddon Matrix. Exhibit 3-4(2) provides an example of this matrix. The Haddon Matrix helps create order when determining which contributing factors influence a crash and which period of the crash the factors influence. The factors listed are not intended to be comprehensive; they are examples only.

The Haddon Matrix is a framework for identifying crash contributing factors.

Exhibit 3-4: Example Haddon Matrix for Identifying Contributing Factors

Period	Human Factors	Vehicle Factors	Roadway/Environment Factors
Before Crash Factors contributing to increased risk of crash	distraction, fatigue, inattention, poor judgment, age, cell phone use, deficient driving habits	worn tires, worn brakes	wet pavement, polished aggregate, steep downgrade, poorly coordinated signal system
During Crash Factors contributing to crash severity	vulnerability to injury, age, failure to wear a seat belt, driving speed, sobriety	bumper heights and energy adsorption, headrest design, airbag operations	pavement friction, grade, roadside environment
After Crash Factors contributing to crash outcome	age, gender	ease of removal of injured passengers	the time and quality of the emergency response, subsequent medical treatment

Considering the crash contributing factors and what period of a crash event they relate to supports the process of identifying appropriate crash reduction strategies. Some examples of how a reduction in crashes and crash severity may be achieved include:

- The behavior of humans;
- The condition of the roadway/environment;
- The design and maintenance of technology including vehicles, roadway and the environment technology;
- The provision of emergency medical treatment, medical treatment technology and post-crash rehabilitation;
- The exposure to travel, or level of transportation demand.

Strategies to influence the above and reduce crash and crash severity may include:

- **Design, Planning and Maintenance** - may reduce or eliminate crashes by improving and maintaining the transportation system, such as modifying signal phasing. Crash severity may also be reduced by selection of appropriate treatments (such as the use of median barriers to prevent head-on collisions).
- **Education** - may reduce crashes by influencing the behavior of humans including public awareness campaigns, driver training programs, and training of engineers and doctors.
- **Policy/Legislation** – may reduce crashes by influencing human behavior and design of roadway and vehicle technology. For example laws may prohibit cell phone use while driving, require minimum design standards, mandate use of helmets, and seatbelts.

- **Enforcement** – may reduce crashes by penalizing illegal behavior such as excessive speeding and drunken driving.
- **Technology Advances** – may reduce crashes and crash severity by minimizing the outcomes of a crash or preempting crashes from occurring altogether. For example, electronic stability control systems in vehicles improve the driver's ability to maintain control of a vehicle. The introduction of "Jaws of Life" tools (for removing injured persons from a vehicle) has reduced the time taken to provide emergency medical services.
- **Demand Management/Exposure reduction** – may reduce crashes by reducing the number of 'events' on the transportation system for which the risk of a crash may arise. For example, increasing the availability of mass transit reduces the number of passenger vehicles on the road and therefore a potential reduction in crash frequency may occur because of less exposure.

A direct relationship between individual contributing factors and particular strategies to reduce crashes does not exist. For example, in a head on crash on a two lane rural road in dry, well illuminated conditions, the roadway may not be considered as a contributing factor. However, the crash may have been prevented if the roadway was a divided road. Therefore while the roadway may not be listed as a contributing factor, changing the roadway design is one potential strategy to prevent similar accidents in the future.

While all of the above strategies play an important role in reducing crashes and crash severity, the majority of these strategies are beyond the scope of the HSM. The HSM focuses on the reduction of crashes and crash severity where it is believed that the roadway/environment is a contributing factor, either exclusively or through interactions with the vehicle and/or the driver.

3.3. DATA FOR CRASH ESTIMATION

This section describes the data that is typically collected and used for the purposes of crash analysis, and the limitations of observed crash data in the estimation of crashes and evaluation of crash reduction programs.

3.3.1. Data Needed for Crash Analysis

Accurate, detailed crash data, roadway or intersection inventory data, and traffic volume data are essential to undertake meaningful and statistically sound analyses. This data may include:

Typical data needs for crash analysis are: crash data, facility data, and traffic volume data.

- **Crash Data:** The data elements in a crash report describe the overall characteristics of the crash. While the specifics and level of detail of this data vary from state to state, in general, the most basic crash data consist of crash location, date and time, crash severity and collision type, and basic information about the roadway, vehicles and people involved.
- **Facility Data:** The roadway or intersection inventory data provide information about the physical characteristics of the accident site. The most basic roadway inventory data typically include roadway classification, number of lanes, length, and presence of medians and

shoulder width. Intersection inventories typically include road names, area type, and traffic control and lane configurations.

- **Traffic Volume Data:** In most cases, the traffic volume data required for the methods in the HSM are annual average daily traffic (AADT). Some organizations may use ADT (average daily traffic) as precise data may not be available to determine AADT. If AADT data are unavailable, ADT can be used to estimate AADT. Other data that may be used for crash analysis includes intersection total entering vehicles (TEV), and vehicle-miles traveled (VMT) on a roadway segment, which is a measure of segment length and traffic volume. In some cases, additional volume data, such as pedestrian crossing counts or turning movement volumes, may be necessary.

The HSM Data Needs Guide(9) provides additional data information. In addition, in an effort to standardize databases related to crash analyses there are two guidelines published by FHWA: The Model Minimum Uniform Crash Criteria (MMUCC); and the Model Minimum Inventory of Roadway Elements (MMIRE). MMUCC (http://www.mmucc.us) is a set of voluntary guidelines to assist states in collecting consistent crash data. The goal of the MMUCC is that with standardized integrated databases, there can be consistent crash data analysis and transferability. MMIRE (http://www.mmire.org) provides guidance on what roadway inventory and traffic elements can be included in crash analysis, and proposes standardized coding for those elements. As with MMUCC, the goal of MMIRE is to provide transferability by standardizing database information.

3.3.2. Limitations of Observed Crash Data Accuracy

This section discusses the limitations of recording, reporting and measuring crash data with accuracy and consistency. These issues can introduce bias and affect crash estimation reliability in ways that are not easily addressed. These limitations are not specific to a particular crash analysis methodology and their implications require consideration regardless of the particular crash analysis methodology used.

Limitations of observed crash data include:

- Data quality and accuracy
- Crash reporting thresholds and the frequency-severity indeterminacy
- Differences in data collection methods and definitions used by jurisdictions

Limitations of typical crash data are summarized in Section 3.3.2.

Data Quality and Accuracy

Crash data are typically collected on standardized forms by trained police personnel and, in some states, by integrating information provided by citizens self-reporting PDO crashes. Not all crashes are reported, and not all reported crashes are recorded accurately. Errors may occur at any stage of the collection and recording of crash data and may be due to:

- **Data entry** - typographic errors;
- **Imprecise entry -** the use of general terms to describe a location;

- **Incorrect entry -** entry of road names, road surface, level of accident severity, vehicle types, impact description, etc.;
- **Incorrect training** -lack of training in use of collision codes;
- **Subjectivity -** Where data collection relies on the subjective opinion of an individual, inconsistency is likely. For example estimation of property damage thresholds, or excessive speed for conditions.

Crash Reporting Thresholds

Reported and recorded crashes are referred to as observed crash data in the HSM. One limitation on the accuracy of observed crash data is that all crashes are not reported. While a number of reasons for this may exist, a common reason is the use of minimum accident reporting thresholds.

Transportation agencies and jurisdictions typically use police accident reports as a source of observed crash records. In most states, crashes must be reported to police when damage is above a minimum dollar value threshold. This threshold varies between states. When thresholds change, the change in observed crash frequency does not necessarily represent a change in long term average crash frequency but rather creates a condition where comparisons between previous years can not be made.

To compensate for inflation, the minimum dollar value for accident reporting is periodically increased through legislation. Typically the increase is followed by a drop in the number of reported crashes. This decrease in reported crashes does not represent an increase in safety. It is important to be aware of crash reporting thresholds and to ensure that a change to reporting thresholds did not occur during the period of study under consideration.

Crash Reporting and the Frequency-Severity Indeterminacy

Not all reportable crashes are actually reported to police and therefore not all crashes are included in a crash database. In addition, studies indicate that crashes with greater severity are reported more reliably than crashes of lower severity. This situation creates an issue called frequency-severity indeterminancy, which represents the difficulty in determining if a change in the number of reported accidents is caused by an actual change in accidents, a shift in severity proportions, or a mixture of the two. It is important to recognize frequency-severity indeterminacy in measuring effectiveness of and selecting countermeasures. No quantitative tools currently exist to measure frequency-severity indeterminacy.

Differences between Crash Reporting Criteria of Jurisdictions

Differences exist between jurisdictions regarding how crashes are reported and classified. This especially affects the development of statistical models for different facility types using crash data from different jurisdictions, and the comparison or use of models across jurisdictions. Different definitions, criteria and methods of determining and measuring crash data may include:

- Crash reporting thresholds
- Definition of terms and criteria relating to crashes, traffic and geometric data

- Crash severity categories

Crash reporting thresholds were discussed above. Different definitions and terms relating to the three types of data (i.e. traffic volume, geometric design, and crash data) can create difficulties as it may be unclear whether the difference is limited to the terminology or whether the definitions and criteria for measuring a particular type of data is different. For example, most jurisdictions use annual average daily traffic (AADT) as an indicator of yearly traffic volume, others use average daily traffic (ADT).

Variation in crash severity terms can lead to difficulties in comparing data between states and development of models which are applicable to multiple states, for example, a fatal injury is defined by some agencies as "any injury that results in death within a specified period after the road vehicle accident in which the injury occurred. Typically the specified period is 30 days."(7) In contrast, World Health Organization procedures, adopted for vital statistics reporting in the United States, use a 12-month limit. Simlarly, juridictions may use differing injury scales or have different severity classifications or groupings of classifications. These differences may lead to the inconsistencies in reported crash severity and the proportion of severe injury to fatalities across jursidictions.

Therefore, the count of reported crashes in a database is partial, may contain inaccurate or incomplete information, may not be uniform for all collision types and crash severities, may vary over time, and may differ from jurisdiction to jurisdiction.

3.3.3. Limitations Due To Randomness and Change

This section introduces regression to the mean concepts and issues associated with changes in site conditions (i.e., physical or traffic volume).

This section discusses the limitations associated with natural variations in crash data and the changes in site conditions. These are limitations due to inherent characteristics of the data itself , not limitations due to the method by which the data is collected or reported. If not considered and accounted for as possible, the limitations can introduce bias and affect crash data reliability in ways that are not easily accounted for. These limitations are not specific to a particular crash analysis methodology and their implications require consideration regardless of the particular crash analysis methodology being used.

Limitations due to randomness and changes include:

- Natural variability in crash frequency
- Regression-to-the-mean and regression-to-the-mean bias
- Variations in roadway characteristics
- Conflict between Crash Frequency Variability and Changing Site Conditions

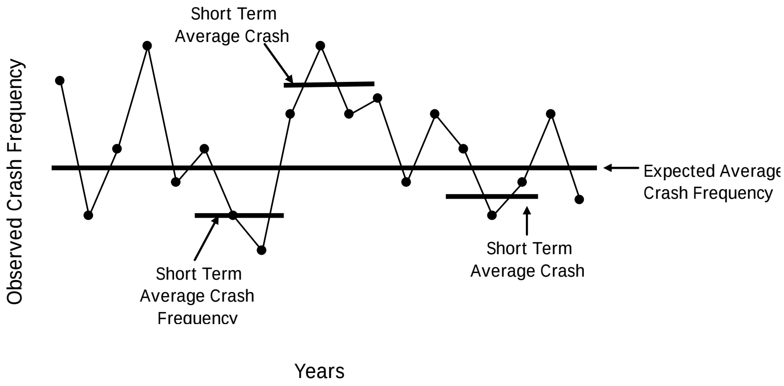
Natural Variability in Crash Frequency

Because crashes are random events, crash frequencies naturally fluctuate over time at any given site. The randomness of accident occurrence indicates that short-term crash frequencies alone are not a reliable estimator of long-term crash frequency. If a three-year period of crashes were used as the sample to estimate crash frequency, it would be difficult to know if this three-year period represents a typically high, average, or low crash frequency at the site.

This year-to-year variability in crash frequencies adversely affects crash estimation based on crash data collected over short periods. The short-term average crash frequency may vary significantly from the long-term average crash frequency. This effect is magnified at study locations with low crash frequencies where changes due to variability in crash frequencies represent an even larger fluctuation relative to the expected average crash frequency.

Exhibit 3-5 demonstrates the randomness of observed crash frequency, and limitation of estimating crash frequency based on short-term observations.

Exhibit 3-5: Variation in Short-Term Observed Crash Frequency



Regression-to-the-Mean and Regression-to-the-Mean Bias

The crash fluctuation over time makes it difficult to determine whether changes in the observed crash frequency are due to changes in site conditions or are due to natural fluctuations. When a period with a comparatively high crash frequency is observed, is statistically probable that the following period will be followed by a comparatively low crash frequency (8). This tendency is known as regression-to-the-mean (RTM), and also applies to the high probability that a low crash frequency period will be followed by a high crash frequency period.

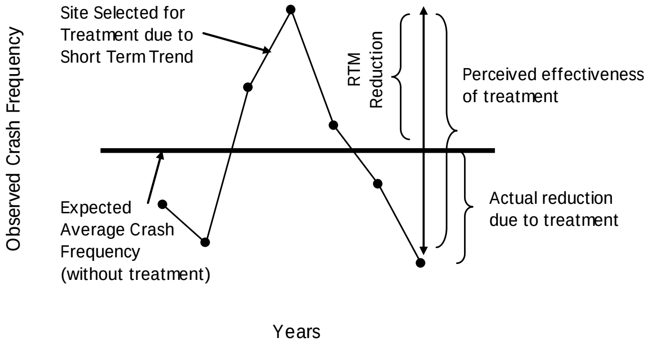
Chapter 4 and Part C of the HSM introduce crash estimation methods that address regression-to-the-mean.

Failure to account for the effects of RTM introduces the potential for "RTM bias", also known as "selection bias". Selection bias occurs when sites are selected for treatment based on short-term trends in observed crash frequency. For example, a site is selected for treatment based on a high observed crash frequency during a very short period of time (e.g. two years). However, the sites long-term crash frequency may actually be substantially lower and therefore the treatment may have been more cost effective at an alternate site. RTM bias can also result in the overestimation or underestimation of the effectiveness of a treatment (i.e., the change in expected average crash frequency). Without accounting for RTM bias, it is not possible to know if an observed reduction in crashes is due to the treatment or if it would have occurred without the modification.

The effect of RTM and RTM bias in evaluation of treatment effectiveness is shown on Exhibit 3-6. In this example, a site is selected for treatment based on its short term crash frequency trend over three years (which is trending upwards). Due to regression-to-the-mean, it is probable that the observed crash frequency will actually decrease (towards the expected average crash frequency) without any treatment. A treatment is applied, which has a beneficial effect (i.e., there is a reduction in crashes due to the treatment). However, if the reduction in crash frequency that would have occurred (due to RTM) without the treatment is ignored the effectiveness of the treatment is perceived to be greater than its actual effectiveness.

The effect of RTM bias is accounted for when treatment effectiveness (i.e., reduction in crash frequency or severity) and site selection is based on a long-term average crash frequency. Because of the short-term year-to-year variability in observed crash frequency, and consequences of not accounting for RTM bias, the HSM focuses on estimating of the ″expected average crash frequency″ as defined in section 3.2.4.

Exhibit 3-6 Regression-to-the-mean (RTM) and RTM Bias



Variations in Roadway Characteristics and Environment

A site’s characteristics, such as traffic volume, weather, traffic control, land use and geometric design, are subject to change over time. Some conditions, such as traffic control or geometry changes at an intersection, are discrete events. Other characteristics, like traffic volume and weather, change on a continual basis.

The variation of site conditions over time makes it difficult to attribute changes in the expected average crash frequency to specific conditions. It also limits the number of years that can be included in a study. If longer time periods are studied (to improve the estimation of crash frequency and account for natural variability and RTM), it becomes likely that changes in conditions at the site occurred during the study period. One way to address this limitation is to estimate the expected average crash frequency for the specific conditions for each year in a study period. This is the predictive method applied in *Part C* of the HSM.

Variation in conditions also plays a role in evaluation of the effectiveness of a treatment. Changes in conditions between a “before” period and an “after” period may make it difficult to determine the actual effectiveness of a particular treatment. This may mean that a treatments effect may be over or under estimated, or unable to be determined. More information about this is included in *Chapter 9*.

Conflict between Crash Frequency Variability and Changing Site Conditions

The implications of crash frequency fluctuation and variation of site conditions are often in conflict. On one hand, the year-to-year fluctuation in crash frequencies tends toward acquiring more years of data to determine the expected average crash frequency. On the other hand, changes in site conditions can shorten the length of time for which crash frequencies are valid for considering averages. This push/pull relationship requires considerable judgment when undertaking large-scale analyses and using crash estimation procedures based on observed crash frequency. This limitation can be addressed by estimating the expected average crash frequency for the specific conditions for each year in a study period, which is the predictive method applied in *Part C* of the HSM.

3.4. EVOLUTION OF CRASH ESTIMATION METHODS

This section provides a brief overview of the evolution of crash estimation methods and their strengths and limitations. The development of new crash estimation methods is associated not only with increasing sophistication of the statistical techniques, but is also due to changes in the thinking about road safety. Additional information is included in Appendix A. The following crash estimation methods are discussed:

- Crash estimation using observed crash frequency and crash rates over a short-term period, and a long term period (e.g., more than 10 years);
- Indirect safety measures for identifying high crash locations. Indirect safety measures are also known as surrogate measures;
- Statistical analysis techniques (specifically the development of statistical regression models for estimation of crash frequency), and statistical methodologies to incorporate observed crash data to improve the reliability of crash estimation models.

3.4.1. Observed Crash Frequency and Crash Rate Methods

Crash frequency and crash rates are often used for crash estimation and evaluation of treatment effectiveness. In the HSM, the historic crash data on any facility (i.e., the number of recorded crashes in a given period) is referred to as the "observed crash frequency".

"Crash rate" is the number of crashes that occur at a given site during a certain time period in relation to a particular measure of exposure (e.g., per million vehicle miles of travel for a roadway segment or per million entering vehicles for an intersection). Crash rates may be interpreted as the probability (based on past events) of being involved in an accident per instance of the exposure measure. For example, if the crash rate on a roadway segment is one crash per one million vehicle miles per year, then a vehicle has a one-in-a-million chance of being in an accident for every mile traveled on that roadway segment. Crash rates are calculated according to Equation 3-2.

$$Crash\ Rate = \frac{Average\ Crash\ Frequency\ in\ a\ Period}{Exposure\ in\ Same\ Period} \qquad (3\text{-}2)$$

Observed crash frequency and crash rates are often used as a tool to identify and prioritize sites in need of modifications, and for evaluation of the effectiveness of treatments. Typically, those sites with the highest crash rate or perhaps with rates higher than a certain threshold are analyzed in detail to identify potential modifications to reduce crashes. In addition, crash frequency and crash rate are often used in conjunction with other analysis techniques, such as reviewing crash records by year, collision type, crash severity, and/or environmental conditions to identify other apparent trends or patterns over time. Chapter 3 Appendix A.3 provides examples of crash estimation using historic crash data.

Advantages in the use of observed crash frequency and crash rates include:

- Understandability –observed crash frequency and rates are intuitive to most members of the public;
- Acceptance – it is intuitive for members of the public to assume that observed trends will continue to occur;
- Limited alternatives – in the absence of any other available methodology, observed crash frequency is the only available method of estimation.

Crash estimation methods based solely on historical crash data are subject to a number of limitations. These include the limitations associated with the collection of data described in section 3.3.2 and 3.3.3.

Also, the use of crash rate incorrectly assumes a linear relationship between crash frequency and the measure of exposure. Research has confirmed that while there are often strong relationships between crashes and many measures of exposure, these relationships are usually non-linear.(1,5,11)

A (theoretical) example which illustrates how crash rates can be misleading is to consider a rural two-lane two-way road with low traffic volumes with a very low observed crash frequency. Additional development may substantially increase the traffic volumes and consequently the number of crashes. However, it is likely that the crash rate may decline because the increased traffic volumes. For example the traffic volumes may increase threefold, but the observed crash frequency may only double, leading to a one third reduction in crash rate. If this change isn’t accounted for, one might assume that the new development made the roadway safer.

Not accounting for the limitations described above may result in ineffective use of limited safety funding. Further, estimating crash conditions based solely on observed crash data limits crash estimation to the expected average crash frequency of an existing site where conditions (and traffic volumes) are likely to remain constant for a long-term period, which is rarely the case. This precludes the ability to estimate the expected average crash frequency for:

- The existing system under different geometric design or traffic volumes in the past (considering if a treatment had not been implemented) or in the future (in considering alternative treatment designs);
- Design alternatives of roadways that have not been constructed.

As the number of years of available crash data increases the risk of issues associated with regression-to-the-mean bias decrease. Therefore, in situations where crashes are extremely rare (e.g., at rail-grade crossings) observed crash frequency or crash rates may reliably estimate expected average crash frequency and therefore can be used as a comparative value for ranking (see Chapter 3 Appendix A.4 for further discussion).

Even when there have been limited changes at a site (e.g., traffic volume, land use, weather, driver demographics have remained constant) other limitations relating to changing contributing factors remain. For example the use of motorcycles may have increased across the network during the study period. An increase in observed motorcycle crashes at the site may be associated with the overall change in levels of motorcycle use across the network rather than in increase in motorcycle crashes at the specific site.

Agencies may be subject to reporting requirements which require provision of crash rate information. The evolution of crash estimation methods introduces new concepts with greater reliability than crash rates, and therefore the HSM does not focus on the use of crash rates. The techniques and methodologies presented in the HSM 1st Edition are relatively new to the field of transportation and will take time to become "best" practice. Therefore it is likely that agencies may continue to be subject to requirements to report crash rates in the near term.

3.4.2. Indirect Safety Measures

Indirect safety measures have also been applied to measure and monitor a site or a number of sites. Also known as surrogate safety measures, indirect safety measures provide a surrogate methodology when accident frequencies are not available because the roadway or facility is not yet in service or has only been in service for a short time; or when crash frequencies are low or have not been collected; or when a roadway or facility has significant unique features. The important added attraction of indirect safety measurements is that they may save having to wait for sufficient accidents to materialize before a problem is recognized and a remedy applied.

Past practices have mostly used two basic types of surrogate measures to use in place of observed crash frequency. These are:

- Surrogates based on events which are proximate to and usually precede the accident event. For example, at an intersection encroachment time, the time during which a turning vehicle infringes on the right of way of another vehicle may be used as a surrogate estimate.
- Surrogates that presume existence of a causal link to expected accident frequency. For example, proportion of occupants wearing seatbelts may be used as a surrogate for estimation of crash severities.

Conflict studies are another indirect measurement of safety. In these studies, direct observation of a site is conducted in order to examine "near-accidents" as an indirect measure of potential crash problems at a site. Because the HSM is focused on quantitative crash information, conflict studies are not included in the HSM.

The strength of indirect safety measures is that the data for analysis is more readily available. There is no need to wait for crashes to occur. The limitations of indirect safety measures include the often unproven relationship between the surrogate events and crash estimation. Chapter 3 Appendix D provides more detailed information about indirect safety measures.

3.4.3. Crash Estimation using Statistical Methods

Statistical models using regression analysis have been developed which address some of the limitations of other methods identified above. These models address RTM bias and also provide the ability to reliably estimate expected average crash frequency for not only existing roadway conditions, but also changes to existing conditions or a new roadway design prior to its construction and use.

As with all statistical methods used to make estimation, the reliability of the model is partially a function of how well the model fits the original data and partially a function of how well the model has been calibrated to local data. In addition to statistical models based on crash data from a range of similar sites, the reliability of crash estimation is improved when historic crash data for a specific site can be incorporated into the results of the model estimation.

A number of statistical methods exist for combining estimates of crashes from a statistical model with the estimate using observed crash frequency at a site or facility. These include:

- Empirical Bayes method (EB Method)
- Hierarchical Bayes method
- Full Bayes method

Jurisdictions may have the data and expertise to develop their own models and to implement these statistical methods. In the HSM, the EB Method is used as part of the predictive method described in *Part C*. A distinct advantage of the EB Method is that, once a calibrated model is developed for a particular site type, the method can be readily applied. The Hierarchical Bayes and Full Bayes method are not used in the HSM, and are not discussed within this manual.

3.4.4. Development and Content of the HSM Methods

Section 3.3 through 3.4.3 discuss the limitations related to the use of observed crash data in crash analysis and some of the various methods for crash estimation which have evolved as the field of crash estimation has matured. The HSM has been developed due to recognition amongst transportation professionals of the need to develop standardized quantitative methods for crash estimation and crash evaluation which address the limitations described in Section 3.3.

The HSM provides quantitative methods to reliably estimate crash frequencies and severities for a range of situations, and to provide related decision making tools to use within the road safety management process. *Part A* of the HSM provides an overview of Human Factors (in *Chapter 2*) and an introduction to the fundamental concepts used in the HSM (Chapter 3). *Part B* of the HSM focuses on methods to establish a comprehensive and continuous roadway safety management process. *Chapter 4* provides numerous performance measures for identifying sites which may respond to improvements. Some of these performance measures use concepts presented in the overview of the *Part C* predictive method presented below. *Chapters 5* through *8* present information about site crash diagnosis, selecting countermeasures, and prioritizing sites. *Chapter 9* presents methods for evaluating the effectiveness of improvements. Fundamentals of the *Chapter 9* concepts are presented in Section 3.7.

Part C of the HSM, overviewed in Section 3.5, presents the predictive method for estimating the expected average crash frequency for various roadway conditions. The material in this part of the HSM will be valuable in preliminary and final design processes.

Finally, *Part D* contains a variety of roadway treatments with accident modification factors (AMFs). The fundamentals of AMFs are described in Section 3.6, with more details provided in the *Part D Introduction and Applications Guidance*.

3.5. PREDICTIVE METHOD IN PART C OF THE HSM

3.5.1. Overview of the Part C Predictive Method

This section is intended to provide the user with a basic understanding of the predictive method found in Part C of the HSM. A complete overview of the method is provided in the Part C Introduction and Application Guidance. The detail method for specific facility types is described in *Chapter 10, 11* and *12* and the EB Method is explained fully in the *Part C* Appendix.

A detailed explanation of the steps for the HSM predictive method is in the Part C Introduction and Applications Guide.

The predictive method presented in *Part C* provides a structured methodology to estimate the expected average crash frequency (by total crashes, crash severity or collision type) of a site, facility or roadway network for a given time period, geometric design and traffic control features, and traffic volumes (AADT). The predictive method also allows for crash estimation in situations where no observed crash data is available or no predictive model is available.

The expected average crash frequency, $N_{expected}$, is estimated using a predictive model estimate of crash frequency, $N_{predicted}$ (referred to as the predicted average crash frequency) and, where available, observed crash frequency, $N_{observed}$. The basic elements of the predictive method are:

- Predictive model estimate of the average crash frequency for a specific site type. This is done using a statistical model developed from data for a number of similar sites. The model is adjusted to account for specific site conditions and local conditions;
- The use of the EB Method to combine the estimation from the statistical model with observed crash frequency at the specific site. A weighting factor is applied to the two estimates to reflect the model's statistical reliability. When observed crash data is not available or applicable, the EB Method does not apply.

Basic Elements of the Predictive Models in Part C

The predictive models in *Part C* of the HSM vary by facility and site type but all have the same basic elements:

- Safety Performance Functions (SPFs): statistical "base" models are used to estimate the average crash frequency for a facility type with specified base conditions.
- Accident Modification Factors (AMFs): AMFs are the ratio of the effectiveness of one condition in comparison to another condition. AMFs are multiplied with the crash frequency predicted by the SPF to account for the difference between site conditions and specified base conditions;
- Calibration factor (C): multiplied with the crash frequency predicted by the SPF to account for differences between the jurisdiction and time period for which the predictive models were developed and the jurisdiction and time period to which they are applied by HSM users.

While the functional form of the SPFs varies in the HSM, the predictive model to estimate the expected average crash frequency $N_{predicted}$, is generally calculated using Equation 3-3.

$$N_{predicted} = N_{SPF\ x} \times (AMF_{1x} \times AMF_{2x} \times \ldots \times AMF_{yx}) \times C_x \tag{3-3}$$

Where,

$N_{predicted}$= predictive model estimate of crash frequency for a specific year on site type *x* (crashes/year);

$N_{SPF\ x}$= predicted average crash frequency determined for base conditions with the Safety Performance Function representing site type *x* (crashes/year);

AMF_{yx} = Accident Modification Factors specific to site type *x*;

C_x = Calibration Factor to adjust for local conditions for site type *x*.

The First Edition of the HSM provides a detailed predictive method for the following three facility types:

- Chapter 10: Rural Two-Lane Two-Way Roads;
- Chapter 11: Rural Multilane Highways;
- Chapter 12: Urban and Suburban Arterials.

This section presents the advantages of the HSM predictive method.

Advantages of the Predictive Method

Advantages of the predictive method are that:

- Regression-to-the-mean bias is addressed as the method concentrates on long-term expected average crash frequency rather than short-term observed crash frequency.
- Reliance on availability of limited crash data for any one site is reduced by incorporating predictive relationships based on data from many similar sites.
- The method accounts for the fundamentally nonlinear relationship between crash frequency and traffic volume.
- The SPFs in the HSM are based on the negative binomial distribution, which are better suited to modeling the high natural variability of crash data than traditional modeling techniques which are based on the normal distribution.

First time users of the HSM who wish to apply the predictive method are advised to read Section 3.5 (this section), read the Part C *Introduction and Applications Guidance*, and then select an appropriate facility type from *Chapter 10, 11*, or *12* for the roadway network, facility or site under consideration.

3.5.2. Safety Performance Functions

Safety Performance Functions (SPFs) are regression equations that estimate the average crash frequency for a specific site type (with specified base conditions) as a function of annual average daily traffic (AADT) and, in the case of roadway segments, the segment length (L). Base conditions are specified for each SPF and may include conditions such as lane width, presence or absence of lighting, presence of turn lanes etc. An example of a SPF (for roadway segments on rural two-lane highways) is shown in Equation 3-4.

$$N_{SPF\ rs} = (AADT) \times (L) \times (365) \times 10^{(-6)} \times e^{(-0.4865)} \qquad (3\text{-}4)$$

Where,

$N_{spf\ rs}$ = estimate of predicted average crash frequency for SPF base conditions for a rural two-lane two-way roadway segment (described in Section 10.6) (crashes/year);

AADT = average annual daily traffic volume (vehicles per day) on roadway segment;

L = length of roadway segment (miles).

While the SPFs estimate the average crash frequency for all crashes, the predictive method provides procedures to separate the estimated crash frequency into components by crash severity levels and collision types (such as run-off-road or rear-end crashes). In most instances, this is accomplished with default distributions of crash severity level and/or collision type. As these distributions will vary between jurisdictions, the estimations will benefit from updates based on local crash severity and collision type data. This process is explained in the *Part C* Appendix. If sufficient experience exists within an agency, some agencies have chosen to use advanced statistical approaches that allow for prediction of changes by severity levels.(6)

The SPFs in the HSM have been developed for three facility types (rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials), and for specific site types of each facility type (e.g. signalized intersections, unsignalized intersections, divided roadway segments and undivided roadway segments). The different facility types and site types for which SPFs are included in the HSM are summarized in Exhibit 3-9.

Exhibit 3-9: Facility Types and Site Types included in Part C

Exhibit 3.9 shows the Safety Performance Functions in Part C.

HSM Chapter	Undivided Roadway Segments	Divided Roadway Segments	Intersections			
			Stop Control on Minor Leg(s)		Signalized	
			3-Leg	4-Leg	3-Leg	4-Leg
10 – Rural Two-Lane Roads	✓	-	✓	✓	-	✓
11 – Rural Multilane Highways	✓	✓	✓	✓	-	✓
12 – Urban and Suburban Arterial Highways	✓	✓	✓	✓	✓	✓

In order to apply a SPF the following information about the site under consideration is necessary:

- Basic geometric and geographic information of the site to determine the facility type and to determine whether a SPF is available for that facility and site type.
- Detailed geometric design and traffic control features conditions of the site to determine whether and how the site conditions vary from the SPF baseline conditions (the specific information required for each SPF is included in *Part C*.
- AADT information for estimation of past periods, or forecast estimates of AADT for estimation of future periods.

SPFs are developed through statistical multiple regression techniques using observed crash data collected over a number of years at sites with similar characteristics and covering a wide range of AADTs. The regression parameters of the SPFs are determined by assuming that crash frequencies follow a negative binomial distribution. The negative binomial distribution is an extension of the Poisson distribution, and is better suited than the Poisson distribution to modeling of crash data. The Poisson distribution is appropriate when the mean and the variance of the data are equal. For crash data, the variance typically exceeds the mean. Data for which the variance exceeds the mean are said to be overdispersed, and the negative binomial distribution is very well suited to modeling overdispersed data. The degree of overdispersion in a negative binomial model is represented by a statistical parameter, known as the *overdispersion parameter* that is estimated along with the coefficients of the regression equation. The larger the value of the overdispersion parameter, the more the crash data vary as compared to a Poisson distribution with the same mean. The overdispersion parameter is used to determine the value of a weight factor for use in the EB Method described in Section 3.5.5.

The SPFs in the HSM must be calibrated to local conditions as described in Section 3.5.4 below and in detail in the *Part C* Appendix. The derivation of SPFs through regression analysis is described in Chapter 3 Appendix B.

3.5.3. Accident Modification Factors

AMFs are the ratio of the expected average crash frequency of a site under one condition (such as a treatment) to the expected average crash frequency of the same site under a different condition. The different condition is often the base condition.

Accident Modification Factors (AMFs) represent the relative change in crash frequency due to a change in one specific condition (when all other conditions and site characteristics remain constant). AMFs are the ratio of the crash frequency of a site under two different conditions Therefore, an AMF may serve as an estimate of the effect of a particular geometric design or traffic control feature or the effectiveness of a particular treatment or condition.

AMFs are generally presented for the implementation of a particular treatment, also known as a countermeasure, intervention, action, or alternative design. Examples include illuminating an unlighted road segment, paving gravel shoulders, signalizing a stop-controlled intersection, or choosing a signal cycle time of 70 seconds instead of 80 seconds. AMFs have also been developed for conditions that are not associated with the roadway, but represent geographic or demographic conditions surrounding the site or with users of the site (e.g., the number of liquor outlets in proximity to the site).

Equation 3-5 shows the calculation of an AMF for the change in expected average crash frequency from site condition ‘a’ to site condition ‘b’.(3)

$$AMF = \frac{Expected\ average\ crash\ frequency\ with\ condition\ 'b'}{Expected\ average\ crash\ frequency\ with\ condition\ 'a'} \qquad (3\text{-}5)$$

AMFs defined in this way for expected crashes can also be applied to comparison of predicted crashes between site condition 'a' and site condition 'b'.

Accident Modification Factor Examples

Example 1

Using a SPF for rural two-lane roadway segments, the expected average crash frequency for existing conditions is 10 injury crashes/year (assume observed data is not available). The base condition is the absence of automated speed enforcement. If automated speed enforcement were installed, the AMF for injury crashes is 0.83. Therefore, if there is no change to the site conditions other than implementation of automated speed enforcement, the estimate of expected average injury crash frequency is 0.83 x 10 = 8.3 crashes/year.

Example 2

The expected average crashes for an existing signalized intersection is estimated through application of the EB Method (using a SPF and observed crash frequency) to be 20 crashes/year. It is planned to replace the signalized intersection with a modern roundabout. The AMF for conversion of the base condition of an existing signalized intersection to a modern roundabout is 0.52. As no SPF is available for roundabouts, the project AMF is applied to the estimate for existing conditions. Therefore, after installation of a roundabout the expected average crash frequency, is estimated to be 0.52 x 20 = 10.4 crashes/year.

The values of AMFs in the HSM are determined for a specified set of base conditions. These base conditions serve the role of site condition 'a' in Equation 3-5. This allows comparison of treatment options against a specified reference condition. Under the base conditions (i.e., with no change in the conditions), the value of an AMF is 1.00. AMF values less than 1.00 indicate the alternative treatment reduces the estimated average crash frequency in comparison to the base condition. AMF values greater than 1.00 indicate the alternative treatment increases the estimated average crash frequency in comparison to the base condition. The relationship between an AMF and the expected percent change in crash frequency is shown in Equation 3-6.

$$\textit{Percent Reduction in Accidents} = 100 \times (1.00 - AMF) \qquad (3\text{-}6)$$

For example,

- If an AMF = 0.90 then the expected percent change is 100% × (1.00 - 0.90) = 10%, indicating a reduction in expected average crash frequency.
- If an AMF = 1.20 then the expected percent change is 100% × (1.00 - 1.20) = -20%, indicating an increase in expected average crash frequency.

The SPFs and AMFs used in the *Part C* predictive method for a given facility type use the same base conditions so that they are compatible.

Application of AMFs

Applications for AMFs include:

- Multiplying an AMF with a crash frequency for base conditions determined with a SPF to estimate predicted average crash frequency for an individual site, which may consist of existing conditions, alternative conditions or new site conditions. The AMFs are used to account for the difference between the base conditions and actual site conditions;
- Multiplying an AMF with the expected average crash frequency of an existing site that is being considered for treatment, when a site-specific SPF applicable to the treated site is not available. This estimates expected average crash frequency of the treated site. For example an AMF for a change in site type or conditions such as the change from an unsignalized intersection to a roundabout can be used if no SPF is available for the proposed site type or conditions;
- Multiplying an AMF with the observed crash frequency of an existing site that is being considered for treatment to estimate the change in expected average crash frequency due to application of a treatment, when a site-specific SPF applicable to the treated site is not available.

Application of an AMF will provide an estimate of the change in crashes due to a treatment. There will be variance in results at any particular location.

Applying Multiple AMFs

The predictive method assumes that AMFs can be multiplied together to estimate the combined effects of the respective elements or treatments. This approach assumes that the individual elements or treatments considered in the analysis are independent of one another. Limited research exists regarding the independence of individual treatments from one another.

AMFs are multiplicative even when a treatment can be implemented to various degrees such that a treatment is applied several times over. For example, a 4% grade can be decreased to 3%, 2%, and so on, or a 6-foot shoulder can be widened by 1-ft, 2-ft, and so on. When consecutive increments have the same degree of effect, Equation 3-7 can be applied to determine the treatment's cumulative effect.

$$AMF\ (\text{for } n \text{ increments}) = [AMF(\text{for one increment})]^{(n)} \tag{3-7}$$

This relationship is also valid for non-integer values of n.

Applying Multiplicative Accident Modification Factors

Example 1

Treatment 'x' consists of providing a left-turn lane on both major-road approaches to an urban four-leg signalized intersection and treatment 'y' is permitting right-turn-on-red maneuvers. These treatments are to be implemented and it is assumed that their effects are independent of each other. An urban four-leg signalized intersection is expected to have 7.9 accidents/year. For treatment t_x, $AMF_x = 0.81$; for treatment t_y, $AMF_y = 1.07$.

What accident frequency is to be expected if treatment x and y are both implemented?

Answer to Example 1

Using Equation 3-7, expected accidents = 7.9 x 0.81 x 1.07 = 6.8 accidents/year.

Example 2

The AMF for single-vehicle run-off-road accidents for a 1% increase in grade is 1.04 regardless of whether the increase is from 1% to 2% or from 5% to 6%. What is the effect of increasing the grade from 2% to 4%?

Answer to Example 2

Using Equation 3-8, expected single-vehicle run-off-road accidents will increase by a factor of $1.04^{(4-2)} = 1.04^2 = 1.08$ = 8% increase.

Multiplication of AMFs in Part C

In the *Part C* predictive method, a SPF estimate is multiplied by a series of AMFs to adjust the estimate of crash frequency from the base condition to the specific conditions present at a site. The AMFs are multiplicative because the effects of the features they represent are presumed to be independent. However, little research exists regarding the independence of these effects, but this is a reasonable assumption based on current knowledge. The use of observed crash frequency data in the EB Method can help to compensate for bias caused by lack of independence of the AMFs. As new research is completed, future HSM editions may be able to address the independence (or lack of independence) of these effects more fully.

Multiplication of AMFs in Part D

AMFs are also used in estimating the anticipated effects of proposed future treatments or countermeasures (e.g., in some of the methods discussed in Section C.8). The limited understanding of interrelationships between the various treatments presented in *Part D* requires consideration, especially when more than three AMFs are proposed. If AMFs are multiplied together, it is possible to overestimate the combined affect of multiple treatments when it is expected that more than one of the treatments may affect the same type of crash. The implementation of wider lanes and wider shoulders along a corridor is an example of a combined treatment where the independence of the individual treatments is unclear, because both treatments are expected to reduce the same crash types. When AMFs are multiplied, the practitioner accepts the assumption that the effects represented by the AMFs are independent of one another. Users should exercise engineering judgement to assess the interrelationship and/or independence of individual elements or treatments being considered for implementation.

Compatibility of Multiple AMFs

Engineering judgment is required to assess inter-relationships of AMFs and to assess the benefits of applying multiple AMFs.

Engineering judgment is also necessary in the use of combined AMFs where multiple treatments change the overall nature or character of the site; in this case, certain AMFs used in the analysis of the existing site conditions and the proposed treatment may not be compatible. An example of this concern is the installation of a roundabout at an urban two-way stop-controlled or signalized intersection. The procedure for estimating the crash frequency after installation of a roundabout (see *Chapter 12*) is to estimate the average crash frequency for the existing site conditions (as a SPF for roundabouts in currently unavailable) and then apply an AMF for a conventional intersection to roundabout conversion. Installing a roundabout changes the nature of the site so that other AMFs applicable to existing urban two-way stop-controlled or signalized intersections may no longer be relevant.

AMFs and Standard Error

The standard error is the standard deviation of the sample mean. The standard deviation is a measure of the spread of the sample data from the sample mean.

The standard error of an estimated value serves as a measure of the reliability of that estimate. The smaller the standard error, the more reliable (less error) the estimate becomes. All AMF values are estimates of the change in expected average crash frequency due to a change in one specific condition. Some AMFs in the HSM include a standard error, indicating the variability of the AMF estimation in relation to sample data values.

Standard error can also be used to calculate a confidence interval for the estimated change in expected average crash frequency. Confidence intervals can be calculated using Equation 3-8 and values from Exhibit 3-10.

$$CI\ (y\%) = AMF_x \pm SE_x \times MSE \tag{3-8}$$

Where,

CI(y%) = the confidence interval for which it is y-percent probable that the true value of the AMF is within the interval;

AMF_x = Accident Modification Factor for condition x;

SE_x= Standard Error of the AMF_x;

MSE = Multiple of Standard Error (see Exhibit 3-10 for values).

Exhibit 3-10: Values for Determining Confidence Intervals using Standard Error

Desired Level of Confidence	Confidence Interval (probability that the true value is within the confidence interval)	Multiples of Standard Error (MSE) to use in Equation 3-8
Low	65-70%	1
Medium	95%	2
High	99.9%	3

AMF Confidence Intervals Using Standard Error

Situation

Roundabouts have been identified as a potential treatment to reduce the estimated average crash frequency for all crashes at a two-way stop-controlled intersection. Research has shown that the AMF for this treatment is 0.22 with a standard error of 0.07.

Confidence Intervals

The AMF estimates that installing a roundabout will reduce expected average crash frequency by 100 x (1 - 0.22) = 78%.

Using a Low Level of Confidence (65-70% probability) the estimated reduction at the site will be 78% ± 1 x 100 x 0.07%, or between 71% and 85%.

Using a High Level of Confidence (i.e., 99.9% probability) the estimated reduction at the site will be 78% ± 3 x 100 x 0.07%, or between 57% and 99%.

As can be seen in the above confidence interval estimates, the higher the level of confidence desired, the greater the range of estimated values.

The Chapter 3 Appendix C provides information of how an AMF and its standard error affect the probability that the AMF will achieve the estimated results.

AMFs in the HSM

AMF values in the HSM are either presented in text (typically where there are a limited range of options for a particular treatment), in formula (typically where treatment options are continuous variables) or in tabular form (where the AMF values vary by facility type, or are in discrete categories). Where AMFs are presented as a discrete value they are shown rounded to two decimal places. Where an AMF is determined using an equation or graph, it must also be rounded to two decimal places. A standard error is provided for some AMFs.

All AMFs in the HSM were selected by an inclusion process or from the results of an expert panel review. *Part D* contains all AMFs in the HSM, and the *Part D Introduction and Applications Guidance* chapter provides an overview of the AMF inclusion process and expert panel review process. All AMFs in *Part D* are presented with some combination of the following information:

- Base conditions, or when the AMF = 1.00;
- Setting and road type for which the AMF is applicable;
- AADT range in which the AMF is applicable;
- Accident type and severity addressed by the AMF;
- Quantitative value of the AMF;
- Standard error of the AMF;
- The source and studies on which the AMF value is based;
- The attributes of the original studies, if known.

Part D contains all AMFs in the HSM. The Part D Introduction and Applications Guidance chapter provides an overview of how the AMFs were developed.

This information presented for each AMF in *Part D* is important for proper application of the AMFs. AMFs in *Part C* are a subset of the *Part D* AMFs. The *Part C* AMFs have the same base conditions (i.e., AMF is 1.00 for base conditions) as their corresponding SPFs in *Part C*.

3.5.4. Calibration

The calibration procedure for the Part C predictive models is presented in the Appendix to Part C.

Crash frequencies, even for nominally similar roadway segments or intersections, can vary widely from one jurisdiction to another. Calibration is the process of adjusting the SPFs to reflect the differing crash frequencies between different jurisdictions. Calibration can be undertaken for a single state, or where appropriate, for a specific geographic region within a state.

Geographic regions may differ markedly in factors such as climate, animal population, driver populations, accident reporting threshold, and accident reporting practices. These variations may result in some jurisdictions experiencing different reported traffic accidents on a particular facility type than in other jurisdictions. In addition, some jurisdictions may have substantial variations in conditions between areas within the jurisdiction (e.g. snowy winter driving conditions in one part of the state and only wet winter driving conditions in another). Methods for calculating calibration factors for roadway segments C_r and intersections C_i are included in the *Part C* Appendix to allow highway agencies to adjust the SPF to match local conditions.

The calibration factors will have values greater than 1.0 for roadways that, on average, experience more accidents than the roadways used in developing the SPFs. The calibration factors for roadways that, on average, experience fewer accidents than the roadways used in the development of the SPF, will have values less than 1.0. The calibration procedures are presented in the Appendix to *Part C*.

Calibration factors provide one method of incorporating local data to improve estimated accident frequencies for individual agencies or locations. Several other default values used in the methodology, such as collision type distributions, can also be replaced with locally derived values. The derivation of values for these parameters is also addressed in the calibration procedure *Part C* Appendix A.1.

3.5.5. Weighting using the Empirical Bayes Method

The EB Method is presented in detail in the Part C Appendix.

Estimation of expected average crash frequency using only observed crash frequency or only estimation using a statistical model (such as the SPFs in *Part C*) may result in a reasonable estimate of crash frequency. However, as discussed in Section 3.4.3, the statistical reliability (the probability that the estimate is correct) is improved by combining observed crash frequency and the estimate of the average crash frequency from a predictive model. While a number of statistical methods exist that can compensate for the potential bias resulting from regression-to the mean, the predictive method in *Part C* uses the empirical Bayes method, herein referred to as the EB Method.

The EB Method uses a weight factor, which is a function of the SPF overdispersion parameter, to combine the two estimates into a weighted average.

The weighted adjustment is therefore dependant only on the variance of the SPF , and is not dependant on the validity of the observed crash data.

The EB Method is only applicable when both predicted and observed crash frequencies are available for the specific roadway network conditions for which the estimate is being made. It can be used to estimate expected average crash frequency for both past and future periods. The EB Method is applicable at either the site-specific level (where crashes can be assigned to a particular location) or the project specific level (where observed data may be known for a particular facility, but cannot be assigned to the site specific level). Where only a predicted or only observed crash data are available, the EB Method is not applicable (however the predictive method provides alternative estimation methods in these cases).

For an individual site the EB Method combines the observed crash frequency with the statistical model estimate using Equation 3-9:

$$N_{expected} = w \text{ x } N_{predicted} + (1 - w) \text{ x } N_{observed} \tag{3-9}$$

Where,

$N_{expected}$ = expected average crashes frequency for the study period.

$N_{predicted}$ = predicted average crash frequency predicted using a SPF for the study period under the given conditions.

w = weighted adjustment to be placed on the SPF prediction.

$N_{observed}$ = observed crash frequency at the site over the study period.

The weighted adjustment factor, w, is a function of the SPF's overdispersion parameter, k, and is calculated using Equation 3-10. The overdispersion parameter is of each SPF is stated in *Part C*.

$$w = \frac{1}{1 + k \times (\sum\limits_{\substack{all\ study\\ years}} N_{Predicted})} \tag{3-10}$$

Where,

k = overdispersion parameter from the associated SPF.

As the value of the overdispersion parameter increases, the value of the weighted adjustment factor decreases. Thus, more emphasis is placed on the observed rather than the predicted crash frequency. When the data used to develop a model are greatly dispersed, the reliability of the resulting predicted crash frequency is likely to be lower. In this case, it is reasonable to place less weight on the predicted crash frequency and more weight on the observed crash frequency. On the other hand, when the data used to develop a model have little overdispersion, the reliability of the resulting SPF is likely to be higher. In this case, it is reasonable to place more weight on the predicted crash frequency and less weight on the observed crash frequency. A more detailed discussion of the EB Methods is presented in the Appendix to *Part C*.

3.5.6. Limitations of Part C Predictive Method

Limitations of the *Part C* predictive method are similar to all methodologies which include regression models: the estimations obtained are only as good as the quality of the model. Regression models do not necessarily always represent cause-and-effect relationships between crash frequency and the variables in the model. For this reason, the variables in the SPFs used in the HSM have been limited to AADT and roadway segment length, because the rationale for these variables having a cause-and-effect relationship to crash frequency is strong. SPFs are developed with observed crash data which, as previously described, has its own set of limitations.

SPFs vary in their ability to predict crash frequency; the SPFs used in the HSM are considered to be among the best available. SPFs are, by their nature, only directly representative of the sites that are used to develop them. Nevertheless, models developed in one jurisdiction are often applied in other jurisdictions. The calibration process provided in the *Part C* predictive method provides a method that agencies can use to adapt the SPFs to their own jurisdiction and to the time period for which they will be applied. Agencies with sufficient expertise may develop SPFs with data for their own jurisdiction for application in the *Part C* predictive method. Development of SPFs with local data is not a necessity for using the HSM. Guidance on development of SPFs using an agency's own data is presented in the *Part C Introduction and Applications Guidance*.

AMFs are used to adjust the crash frequencies predicted for base conditions to the actual site conditions. While multiple AMFs can be used in the predictive method, the interdependence of the effect of different treatment types on one another is not fully understood and engineering judgment is needed to assess when it is appropriate to use multiple AMFs (see Section 3.5.3).

3.6. APPLICATION OF THE HSM

The HSM provides methods for crash estimation for the purposes of making decisions relating to the design, planning, operation and maintenance of roadway networks.

These methods focus on the use of statistical methods in order to address the inherent randomness in crashes. Users do not need to have detailed knowledge of statistical analysis methods in order to understand and use the HSM. However, its use does require understanding of the following general principles:

- Observed crash frequency is an inherently random variable and it is not possible to predict the value for a specific period. The HSM estimates refer to the expected average crash frequency that would be observed if a site could be maintained under consistent conditions for a long-term period, which is rarely possible.
- Calibration of SPFs to local state conditions is an important step in the predictive method. Local and recent calibration factors may provide improved calibration.
- Engineering judgment is required in the use of all HSM procedures and methods, particularly selection and application of SPFs and AMFs to a given site condition.
- Errors and limitations exist in all crash data which affects both the observed crash data for a specific site and the models developed.
- Development of SPFs and AMFs requires understanding of statistical regression modeling and crash analysis techniques. The HSM does not provide sufficient detail and methodologies for users to develop their own SPFs or AMFs.

3.7. EFFECTIVENESS EVALUATION

3.7.1. Overview of Effectiveness Evaluation

Effectiveness evaluation is the process of developing quantitative estimates of the effect a treatment, project, or a group of projects has on expected average crash frequency. The effectiveness estimate for a project or treatment is a valuable piece of information for future decision-making and policy development. For instance, if a new type of treatment was installed at several pilot locations, the treatment's effectiveness evaluation can be used to determine if the treatment warrants application at additional locations.

Effectiveness evaluation may include:

- Evaluating a single project at a specific site to document the effectiveness of that specific project;
- Evaluating a group of similar projects to document the effectiveness of those projects;
- Evaluating a group of similar projects for the specific purpose of quantifying an AMF for a countermeasure;
- Assessing the overall effectiveness of specific types of projects or countermeasures in comparison to their costs.

Effectiveness evaluations may use several different types of performance measures, such as a percentage reduction in crash frequency, a shift in the proportions of crashes by collision type or severity level, an AMF for a treatment, or a comparison of the benefits achieved to the cost of a project or treatment.

As described in Section 3.3, various factors can limit the change in expected average crash frequency at a site or across a cross-section of sites that can be attributed to an implemented treatment. Regression-to-the-mean bias, as described in Section 3.3.3., can affect the perceived effectiveness (i.e., over or under estimate effectiveness) of a particular treatment if the study does not adequately account for the variability of observed crash data. This variability also necessitates acquiring a statistically valid sample size to validate the calculated effectiveness of the studied treatment.

Effectiveness evaluation techniques are presented in *Chapter 9*. The chapter presents statistical methods which provide improved estimates of the crash reduction benefits as compared to simple before-after studies. Simple before-after studies compare the count of crashes at a site before a modification to the count of crashes at a site after the modification to estimate the benefits of an improvement. This method relies on the (usually incorrect) assumption that site conditions have remained constant (e.g. weather, surrounding land use, driver demographics) and does not account for regression-to-the-mean bias. Discussion of the strengths and weaknesses of these methods are presented in *Chapter 9*.

Methods for safety effectiveness evaluation are presented in Chapter 9.

3.7.2. Effectiveness Evaluation Study Types

There are three basic study designs that can be used for effectiveness evaluations:

- Observational before/after studies
- Observational cross-sectional studies

- Experimental before/after studies

In observational studies, inferences are made from data observations for treatments that have been implemented in the normal course of the efforts to improve the road system. Treatments are not implemented specifically for evaluation. By contrast, experimental studies consider treatments that have been implemented specifically for evaluation of effectiveness. In experimental studies, sites that are potential candidates for improvement are randomly assigned to either a treatment group, at which the treatment of interest is implemented, or a comparison group, at which the treatment of interest is not implemented. Subsequent differences in crash frequency between the treatment and comparison groups can then be directly attributed to the treatment. Observational studies are much more common in road safety than experimental studies, because highway agencies operate with limited budgets and typically prioritize their projects based on benefits return. In this sense, random selection does not optimize investment selection and therefore agencies will typically not use this method, unless they are making system wide application of a countermeasure, such as rumble strips. For this reason, the focus of the HSM is on observational studies. The two types of observational studies are explained in further detail below.

Observational Before/After Studies

The scope of an observational before/after study is the evaluation of a treatment when the roadways or facilities are unchanged except for the implementation of the treatment. For example, the resurfacing of a roadway segment generally does not include changes to roadway geometry or other conditions. Similarly, the introduction of a seat belt law does not modify driver demography, travel patterns, vehicle performance or the road network. To conduct a before/after study, data are generally gathered from a group of roadways or facilities comparable in site characteristics where a treatment was implemented. Data are collected for specific time periods before and after the treatment was implemented. Crash data can often be gathered for the "before" period after the treatment has been implemented. However, other data, such as traffic volumes, must be collected during both the "before" and the "after" periods if necessary.

The crash estimation is based on the "before" period. The estimated expected average crash frequency based on the "before" period crashes is then adjusted for changes in the various conditions of the "after" period to predict what expected average crash frequency would have been had the treatment not been installed.

Observational Cross-Sectional Studies

The scope of an observational cross-sectional study is the evaluation of a treatment where there are few roadways or facilities where a treatment was implemented, and there are many roadways or facilities that are similar except they do not have the treatment of interest. For example, it is unlikely that an agency has many rural two-lane road segments where horizontal curvature was rebuilt to increase the horizontal curve radius. However, it is likely that an agency has many rural two-lane road segments with horizontal curvature in a certain range, such as 1,500- to 2,000-foot range, and another group of segments with curvature in another range, such as 3,000 to 5,000 feet. These two groups of rural two-lane road segments could be used in a cross-sectional study. Data are collected for a specific time period for both groups. The crash estimation based on the accident frequencies for one group is compared with the crash estimation of the other group. It is, however, very difficult to adjust for differences in the various relevant conditions between the two groups.

3.8. CONCLUSIONS

Chapter 3 summarizes the key concepts, definitions, and methods presented in the HSM. The HSM focuses on crashes as an indicator of safety, and in particular is focused on methods to estimate the crash frequency and severity of a given site type for given conditions during a specific period of time.

Crashes are rare and randomly occurring events which result in injury or property damage. These events are influenced by a number of interdependent contributing factors which affect the events before, during and after a crash.

Crash estimation methods are reliant on accurate and consistent collection of observed crash data. The limitations and potential for inaccuracy inherent in the collection of data apply to all crash estimation methods and need consideration.

As crashes are rare and random events, the observed crash frequency will fluctuate year to year due to both natural random variation and changes in site conditions which affect the number of crashes. The assumption that the observed crash frequency over a short period represents a reliable estimate of the long-term average crash frequency fails to account for the non-linear relationships between crashes and exposure. The assumption also does not account for regression-to-the-mean (RTM) bias (also known as selection bias), resulting in ineffective expenditure of limited safety funds and over (or under) estimation of the effectiveness of a particular treatment type.

In order to account for the effects of RTM bias, and the limitations of other crash estimations methods (discussed in Section 3.4), the HSM provides a predictive method for the estimation of the expected average crash frequency of a site, for given geometric and geographic conditions, in a specific period for a particular AADT.

Expected average crash frequency is the crash frequency expected to occur if the long-term average crash frequency of a site could be determined for a particular type of roadway segment or intersection with no change in the sites conditions. The predictive method (presented in *Part C*) uses statistical models, known as SPFs, and accident modification factors, AMFs, to estimate predicted average crash frequency. These models must be calibrated to local conditions to account for differing crash frequencies between different states and jurisdictions. When appropriate, the statistical estimate is combined with the observed crash frequency of a specific site using the EB Method, to improve the reliability of the estimation. The predictive method also allows for estimation using only SPFs, or only observed data in cases where either a model or observed data in not available.

Effectiveness evaluations are conducted using observational before/after and cross-sectional studies. The evaluation of a treatment's effectiveness involves comparing the expected average crash frequency of a roadway or site with the implemented treatment to the expected average crash frequency of the roadway element or site had the treatment not been installed.

3.9. REFERENCES

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