NCHRP Project 17-89A

Safety Prediction Model for Freeway Facilities with High Occupancy (HO) Lanes

Safety Implementation Guide

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Summary

The High Occupancy Vehicle (HOV)/ High Occupancy Toll (HOT) Safety Implementation Guide provides transportation practitioners with the necessary information to make consistent, data-driven decisions for evaluating the safety performance of freeway facilities with HOV and HOT lanes. This guide can be used to evaluate the safety performance of freeway facilities with HOV/HOT lanes. The predictive method provided in Chapter 18 of the Highway Safety Manual (HSM) Supplement can be used to evaluate a freeway facility without HOV or HOT lanes. Together, they can be used to evaluate the change in crash potential associated with the addition of an HOT or HOT lane, provided that the analysis jurisdiction has calibration factors for both predictive methods.

This guide provides the necessary definitions and identifies the key components needed to evaluate base freeway segments and speed-change lanes with HOV/HOT lanes. Further, this guide provides details on the predictive method for HOV/HOT lanes, two example problems implementing the method, and an overview of the spreadsheet implementation tool. Practitioners should know that, while the Chapter 18 method uses a bi-directional approach, the predictive method described in this guide provides a directional approach for crash prediction on freeway facilities with HOV/HOT lanes. The final component of this guide includes a brief overview of using the results from the crash prediction method.

Chapter 1. Guide Overview

1.1 INTRODUCTION AND PURPOSE

The High Occupancy Vehicle (HOV)/ High Occupancy Toll (HOT) (herein referred to collectively as HO) Safety Implementation Guide provides transportation practitioners with the necessary information to make consistent, data-driven decisions for evaluating the safety performance of freeway facilities with HO lanes. This guide can be used to evaluate the safety performance of freeway facilities with HO lanes. The predictive method provided in Chapter 18 of the Highway Safety Manual (HSM) Supplement can be used to evaluate a freeway facility without HOV or HOT lanes. Together, they can be used to evaluate the change in crash potential associated with the addition of an HOT or HOT lane, provided that the analysis jurisdiction has calibration factors for both predictive methods. Further, analysts should take note that the predictive method for freeway facilities with HO lanes uses a directional approach, while the predictive method in HSM Chapter 18 employs a bi-directional approach.

This guide provides practitioners with a methodology for predicting the average crash frequency (by severity and type) for freeway facilities with continuous access, buffer-separated, or barrier/pylon separated HO lanes. This methodology currently does not address reversible HO lanes. See Table 1 in Section 2.2 for further details on the types of HO lanes addressed by the predictive method.

The predictive method applies to basic freeway segments, entrance speed-change lanes, and exit speed-change lanes. As with other facility types, the predictive method consists of safety performance functions (SPFs) and adjustment factors (AFs). Additionally, the predictive method includes severity distribution functions (SDFs) to predict crash frequency by severity level.

This guide provides practitioners with key definitions, application scope, step-by-step instructions on using the predictive method, and two example problems. This guide also includes details on calibrating the predictive models, potential applications, and limitations of the predictive method. Further, this guide provides details on using the implementation spreadsheet to apply the predictive method.

1.2 TARGET AUDIENCE

The target audience of this guide is transportation professionals charged with evaluating the safety performance for freeway facilities with current or proposed HO lanes, including traffic and safety engineers, designers, and planners. This guide assumes that these practitioners are familiar with basic concepts from the HSM.

1.3 STRUCTURE OF THE GUIDE

This guide is organized into four chapters as follows:

1. Guide overview. This chapter provides details on the purpose of the guide, target audience, and structure of the guide.
2. Safety prediction method for freeway facilities with HO lanes. This chapter is based on the proposed text for the HSM and provides specific details for using the safety prediction method. Section 2.1 provides details on the components of the predictive method and where they are located within the text.

3. Overview of implementation tool. This chapter provides details needed to use the accompanying spreadsheet tool.
4. Using results. This chapter provides details on using the results of the predictive method.

Chapter 2. Safety Prediction Method for Freeway Facilities with HO Lanes

2. 1 OVERVIEW

This chapter presents the predictive method for freeways with either HOV lanes or HOT lanes. It includes the following information:

1. **Introduction**: Section 2.2 introduces the predictive method as a tool for evaluating the crash potential of a freeway facility with HOV or HOT lanes.
2. **Overview of the Predictive Method**: Section 2.3 provides a general description of the predictive method's analytic framework and application scope.
3. **Definitions and Predictive Model Overview**: Section 2.4 provides the information needed to determine whether a freeway facility of interest is addressed by the predictive method. It describes the different site types to which the predictive method can be applied. These site types include basic segments and speed-change lanes. This section also introduces the predictive model for each site type.
4. **Predictive Method Overview and Data Needs**: Section 2.5 provides a step-by-step overview of the predictive method. It also describes the data needed to apply the predictive method.
5. **Segmentation and Crash Assignment**: Section 2.6 provides guidance on dividing the freeway facility into one or more study sites. It also describes how to assign crashes to individual site types.
6. **Safety Prediction Model for Freeway Segments**: Section 2.7 describes the safety prediction model for freeway segments with HOV or HOT lanes. The model components addressed in this section include SPFs, SPF AFs, SDFs, and crash type distributions.
7. **Safety Prediction Model for Speed-Change Lanes**: Section 2.8 describes the safety prediction model for freeway speed-change lane sites with HOV or HOT lanes. The model components addressed in this section include SPFs, AFs, severity distributions, and crash type distributions.
8. **Calibration of Models**: Section 2.9 provides information about the calibration factors in the predictive models and the need for practitioners to calibrate these models to local conditions.
9. **Limitations of Predictive Method**: Limitations of the predictive method are presented in Section 2.10. This information is intended to help the analyst identify site conditions for which the method is most applicable.
10. **Sample Problems**: Section 2.13 presents four sample problems that illustrate the use of the models in a range of situations.

2.2 INTRODUCTION

The predictive method for freeways with HOV or HOT lanes provides a structured methodology to estimate the average crash frequency (in total, by crash type, or by crash severity) for a freeway with HOV or HOT lanes and other known characteristics. An estimate can be made of average crash frequency for a prior time period (i.e., what did or would have occurred) or a future time period (i.e., what is expected to occur). The estimated average crash frequency includes the crashes that occur in the general-purpose (GP) lanes plus those that occur in the HOV or HOT lanes. The development of the predictive method described in this chapter is documented by Himes et al. *(1)*.

The predictive method described in this chapter is used to evaluate sites serving *one direction of travel* along the freeway. This approach is in contrast to that used in Chapter 18 of the 2014 supplement to the HSM (*2*). The method in Chapter 18 is used to evaluate sites that serve both directions of travel along the freeway. If an analyst desires to evaluate both directions of travel using the method described in this chapter, they will need to initially use it to evaluate the sites serving one direction of travel and then subsequently use it to evaluate the sites serving the opposing direction of travel. The results for each direction can be added together to facilitate the evaluation both directions combined.

The predictive method described in this chapter is used to evaluate a freeway facility with HOV or HOT lanes serving the subject direction of travel. This facility can represent an existing freeway, a design alternative for an existing freeway, or a new freeway.

Table 1 identifies a wide range of HOV and HOT design configurations and their application frequency on freeways with HOV or HOT lanes. The possible design configurations are indicated in the last four columns of the table using the various combinations of lateral separation, access type, and lane orientation. Those combinations that are associated with a cell having a white background are addressed by the predictive method. Those combinations associated with a cell that has a grey shaded background are not currently addressed by the predictive method.

Table 1. HOV and HOT lane design configurations and application frequency.

Lateral Separation	HOV and HOT Access Type	HOV and HOT Application Frequency by Lane Orientation [a, b]			
		Concurrent Lane	Separate Roadway	Reversible Lane	Contraflow Lane
Lane line	Continuous (dashed)	Often used; addressed by method	—	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	—
Flush buffer	Continuous (dashed)	Occasionally used	—	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	—
Pylon buffer	Grade-separated entrance and exit points	—	Often used	—	—
	At-grade entrance and exit zones	Often used; addressed by method	—	—	Often used
Barrier	Grade-separated entrance and exit points	—	Often used	Often used	—
	At-grade entrance and exit zones	Often used; addressed by method	—	Often used	Often used

[a] Predictive method addresses combinations associated with a cell having a white background.
[b] "—" identifies combinations not used (or rarely used).

2.3 OVERVIEW OF THE PREDICTIVE METHOD

2.3.1 General Description

The *predictive method* includes one or more predictive models and an 18-step procedure for estimating the average crash frequency for a roadway network, facility, or site. A *site* is either (a) one direction of travel on a freeway segment or (b) a freeway speed-change lane (inclusive of the adjacent freeway lanes). A *freeway speed-change lane* is an uncontrolled terminal between a ramp and one side of a freeway *(3, p. 10-103)*. For evaluation purposes, a *facility* can be considered to consist of a contiguous set of individual sites. Similarly, for evaluation purposes, a roadway *network* can be considered to consist of a number of contiguous facilities.

The predictive method includes a predictive model for freeway segments and a predictive model for freeway speed-change lane sites. Each *predictive model* typically consists of an SPF, one or more AFs, a calibration factor, a severity distribution, and a crash type distribution. The severity distribution is computed using a severity distribution function. The predictive model is used to compute the predicted average crash frequency of a specified crash type and severity level. The *predictive model equation* consists of the SPF, AFs, and calibration factor.

The predictive method is used to estimate the average number of crashes for an individual site. This estimate can be summed for all sites to compute the average number of crashes for an entire facility or network. The estimate represents a given time period of interest (in years) during which the geometric design and traffic control features are unchanged and traffic volumes are known or forecasted. The average crash frequency is obtained by dividing the average number of crashes during the time period of interest by the number of years during this time period.

The prediction from the predictive model can be combined with observed crash data using the empirical Bayes (EB) method. This combination produces a more reliable estimate of the average crash frequency than is obtained from the predictive model alone. This estimate is referred to as the "expected" average crash frequency. Guidance for applying the EB Method is provided in the appendix for Part C of the HSM (*4*).

2.3.2 Predictive Model Framework

The predictive model equations are of the general form shown in Equation 1.

$$N_{p,w,x,y,z} = N_{spf,w,x,y,z} \times \left(AF_{1,w,x,y,z} \times AF_{2,w,x,y,z} \times \ldots \times AF_{m,w,x,y,z}\right) \times C_{w,x,y,z} \quad (1)$$

where

$N_{p,w,x,y,z}$ = predicted average crash frequency for a specific year for site type w, cross section x, crash type y, and severity z (crashes/yr);

$N_{spf,w,x,y,z}$ = predicted average crash frequency determined for base conditions of the SPF developed for site type w, cross section x, crash type y, and severity z (crashes/yr);

$AF_{m,w,x,y,z}$ = adjustment factors specific to site type w, cross section x, crash type y, and severity z for geometric design and traffic control feature m; and

$C_{w,x,y,z}$ = calibration factor to adjust SPF for local conditions for site type w, cross section x, crash type y, and severity z.

The crash type distribution can be used with the predictive model equations to quantify the crash frequency for each of several crash types. Similarly, the severity distribution can be used to quantify crash frequency by the following severity levels: fatal *K*, incapacitating injury *A*, non-incapacitating injury *B*, and possible injury *C*. In this document, a "fatal-or-injury (FI) crash" is any crash designated has having a *K*, *A*, *B*, or *C* severity level.

The variables that comprise the predictive models include a series of subscripts to describe the conditions to which they apply. These subscripts are described in detail in later sections of this chapter. For this section, it is sufficient to use "placeholder" subscripts such as *w, x, y, z*, and *m*. The meaning of each subscript is described in the following list.

- *w* is a placeholder for specific site-type subscripts that define the equation's application (e.g., it is replaced with "*fs*" when needed to indicate that the equation applies to a freeway segment).
- *x* is a placeholder for segment cross-section subscripts (e.g., number of GP through lanes).
- *y* is a placeholder for crash type subscripts.
- *z* is a placeholder for crash severity subscripts.
- *m* is a placeholder for a specific geometric design or traffic control feature.

An overview of the predictive models is provided in Section 2.4.

2.3.3. Application Scope

Applicable to Urban Freeways with Concurrent HOV or HOT Lanes. As indicated by Table 1, the predictive method is applicable to the evaluation of urban freeways with one or more concurrent HOV or HOT lanes. The method does not differentiate between HOV or HOT operation. The HOV or HOT lanes must be located to the left of the GP lanes and have one of the design configurations identified in the following list:

- Lane line lateral separation with continuous access or with limited access via at-grade entrance/exit zones.
- Flush buffer lateral separation with limited access via at-grade entrance/exit zones.
- Pylon buffer lateral separation with limited access via at-grade entrance/exit zones.
- Barrier separation with limited access via at-grade entrance/exit zones.

Projects Adding HOV or HOT Lanes. The predictive method described in this chapter can be used to evaluate a freeway facility with one or more HOV or HOT lanes. The predictive method provided in Chapter 18 of the 2014 supplement to the HSM (*2*) can be used to evaluate a freeway facility without HOV or HOT lanes. Together, they can be used to evaluate the change in crash potential associated with the addition of an HOT or HOT lane. However, the predictive models provided in Chapter 18 and those described in this chapter were developed using data from freeways in different states and different time periods. When the predictions from these models are to be compared or combined, both sets of models *must* be calibrated for the region of interest to ensure that the results are reliable. Guidance is provided in Section 2.11.2 for using Chapter 18 to evaluate one travel direction of a freeway.

Weaving Section Analysis. The predictive method was developed using data for freeways with and without weaving. Several weaving section types (i.e., configurations) were represented in the data. However, only the "one-sided Type C weaving section" was found to be associated with a change in crash frequency, relative to non-weaving sections. The *one-sided Type C weaving* *section* has the following characteristics: (a) one of the two weaving movements can be made without making any lane changes, (b) the other weaving movement requires two or more lane changes, and (c) the ramp entrance and ramp exit associated with the weaving section are located on the right side of the freeway (as shown in Figure 6). Freeways with other weaving section types can be evaluated using this method; however, the method does not include AFs that explicitly address these configurations.

Alternative Cross Section Analysis. The predictive method was developed using data for freeways with lane widths commonly in the range of 11 to 12 feet. However, a correlation between average lane width and crash frequency was not confirmed through statistical analysis of the data. As a result, the method does not include an AF that explicitly addresses lane width. Alternative cross sections can be evaluated with the method provided that the average lane width is in the range of 11 to 12 feet.

Not Applicable to Left-Side Ramps. The predictive method described in this chapter cannot be used to evaluate the safety influence of speed-change lanes that provide left-side access to the GP lanes.

Not Able to Predict HOV- or HOT-Related Crash Frequency. The estimated average crash frequency obtained from the predictive method includes the crashes that occur in the GP lanes plus those that occur in the HOV or HOT lanes. It does not predict the frequency of just the HOV- or HOT-related crashes. The report by Fitzpatrick and Avelar *(5)* provides some information about the distribution of crashes between the HOV or HOT lanes and the GP lanes. The information in this report may be useful to the analyst desiring some insight as to the frequency of just the HOV- or HOT-related crashes.

2.4 DEFINITIONS AND PREDICTIVE MODEL OVERVIEW

This section provides the definitions of the facility and site types addressed by the predictive method. It also describes the predictive models for each of the site types.

2.4.1 Definition of HOV/HOT Freeway Facility and Site Types

The predictive method applies to sites that comprise an urban freeway with concurrent HOV or HOT lanes. Freeway facilities have fully-restricted access control and grade separation with all intersecting roads. Freeways are accessed only through grade-separated interchanges. Roads having at-grade access should be analyzed as rural highways, suburban arterials, or urban arterials. These facility types are addressed in Chapters 10, 11, and 12 of the HSM (*4*).

The site types addressed by the predictive method are identified in the following list.

- Basic freeway segment with two to seven GP through lanes and one to four concurrent HOV/HOT lanes in the subject travel direction.
- Speed-change lane site (and adjacent through lanes) providing right-side freeway access for an entrance ramp or an exit ramp.

In the predictive method, a *freeway segment* is defined as a length of freeway consisting of two or more GP through lanes with a continuous cross section providing one direction of travel that is separated from the opposing travel lanes by a median.

In the predictive method, a *speed-change lane site* is defined as the one-directional length of freeway located (a) between the marked gore and taper points of the speed-change lane associated with a ramp merge or diverge, and (b) on the same side of the freeway as the merge or diverge area (the location of the gore and taper points are identified in subsequent figures; e.g., Figure 3). In other words, a speed-change lane site has a length that is less than or equal to that of the speed-change lane and a lateral extent that includes the speed-change lane, adjacent shoulders, adjacent through lanes serving the same travel direction as the speed-change lane, and median.

A *GP through lane* is defined as a lane that serves vehicles of all types during all hours of the day. The lane passes through the site. A GP lane that is dropped by ramp within (or just beyond) the site is not a through lane. An HOV or HOT lane is not considered to be a GP through lane. More generally, a managed lane is not considered to be a GP through lane.

An *HOV or HOT (HO) lane* is defined as a lane that serves designated high-occupancy vehicles during some (or all) of the hours of each day. The lane passes through the site. The HO lane is located between the median and the inside GP through lane. It is a type of managed lane.

Table 2 identifies the urban freeway segment configurations for which SPFs have been developed.

Table 2. SPFs for freeway segments with HOV or HOT lanes.

Site Type (*w*)	Cross Section (*x*)	Crash Type (*y*)	Crash Severity (*z*)	SPF
Freeway segment (*fs*)	Two GP through lanes (2)	Multiple vehicle (*mv*)	All severities (*as*)	$N_{spf,fs,2,mv,as}$
		All types (*at*)	All severities (*as*)	$N_{spf,fs,2,at,as}$
	Three or more GP through lanes (3+)	Multiple vehicle (*mv*)	All severities (*as*)	$N_{spf,fs,3+,mv,as}$
		All types (*at*)	All severities (*as*)	$N_{spf,fs,3+,at,as}$

Table 3 identifies the urban speed-change lane configurations for which SPFs have been developed.

Table 3. SPFs for speed-change lanes on freeways with HOV or HOT lanes.

Site Type (*w*)	Cross Section (*x*)	Crash Type (*y*)	Crash Severity (*z*)	SPF
Ramp entrance speed-change lane (*en*)	All cross sections (*ac*)	Multiple vehicle (*mv*)	All severities (*as*)	$N_{spf,en,ac,mv,as}$
		All types (*at*)	All severities (*as*)	$N_{spf,en,ac,at,as}$
Ramp exit speed-change lane (*ex*)	All cross sections (*ac*)	Multiple vehicle (*mv*)	All severities (*as*)	$N_{spf,ex,ac\ ,mv,as}$
		All types (*at*)	All severities (*as*)	$N_{spf,ex,ac,at,as}$

2.4.2 Predictive Model for Freeway Segments with HOV or HOT Lanes

The predictive model for freeway segments is used to compute the predicted average crash frequency of a freeway segment (the prediction does not include crashes that occur in a speed-change lane site).

The SPFs for freeway segments are presented in Section 2.7.1. The associated AFs are presented in Section 2.7.2, the associated severity distributions are presented in Section 2.7.3, and the associated crash type distributions are presented in Section 2.7.4. Guidance for establishing the value of the calibration factor is described in Section 2.9.

The predictive model for freeway segments is presented in Equations 2 to 5. It consists of two predictive model equations (i.e., Equations 2 and 4) which predict total crash frequency (i.e., all crash types and severities) and multiple-vehicle crash frequency of all severities, respectively. Single-vehicle crash frequency of all severities is computed by subtracting multiple-vehicle crash frequency from total crash frequency using Equation 5.

$$N_{p,fs,n,at,as} = C_{fs,ac,at,as} \times N_{spf,fs,n,at,as} \times \left(AF_{1,fs,ac,at,as} \times \ldots \times AF_{m,fs,ac,at,as}\right) \tag{2}$$

$$N_{p,fs,n,mv,as} = \min\left[N_{p,fs,n,at,as}, N'_{p,fs,n,mv,as}\right] \tag{3}$$

$$N'_{p,fs,n,mv,as} = C_{fs,ac,mv,as} \times N_{spf,fs,n,mv,as} \times \left(AF_{1,fs,ac,mv,as} \times \ldots \times AF_{m,fs,ac,mv,as}\right) \tag{4}$$

$$N_{p,fs,n,sv,as} = N_{p,fs,n,at,as} - N_{p,fs,n,mv,as} \tag{5}$$

where

$N_{p,fs,n,y,as}$ = predicted average crash frequency of a freeway segment with *n* lanes, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$N'_{p,fs,n,mv,as}$ = unadjusted predicted average crash frequency of a freeway segment with *n* lanes, multiple-vehicle crash type *mv*, and all severities *as* (crashes/yr);

$N_{spf,fs,n,y,as}$ = predicted average crash frequency of a freeway segment with base conditions, *n* lanes, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$AF_{m,fs,ac,y,as}$ = adjustment factor associated with feature *m* in a freeway segment, any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*; and

$C_{fs,ac,y,as}$ = calibration factor for freeway segments with any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*.

Equation 3 shows that the multiple-vehicle crash frequency is computed as the smaller of the computed total crash frequency $N_{p,fs,n,at,as}$ and the unadjusted multiple-vehicle crash frequency $N'_{p,fs,n,mv,as}$. By definition, the multiple-vehicle crash frequency cannot exceed the total crash frequency. However, this relationship may not hold for some conditions because the underlying models are based on a regression analysis of observed crash data. For these relatively rare conditions, the single-vehicle crash frequency is implied to be very small and is assumed to equal 0.0 crashes per year.

2.4.3 Predictive Model for Freeway Speed-Change Lanes with HOV or HOT Lanes

The predictive model for speed-change lane sites is used to estimate the predicted average crash frequency of a speed-change lane site (the prediction does not include crashes that occur in a freeway segment).

The SPFs for speed-change lane sites are presented in Section 2.8.1. The associated AFs are presented in Section 2.8.2, the associated severity distributions are presented in Section 2.8.3, and the associated crash type distributions are presented in Section 2.8.4. Guidance for establishing the value of the calibration factor is described in Section 2.9.

The predictive model for ramp entrance speed-change lane sites is presented in Equation 6 to 9. It consists of two predictive model equations (i.e., Equations 6 and 8) which predict total crash frequency (i.e., all crash types and severities) and multiple-vehicle crash frequency of all severities, respectively. Single-vehicle crash frequency of all severities is computed by subtracting multiple-vehicle crash frequency from total crash frequency using Equation 9.

$$N_{p,en,ac,at,as} = C_{en,ac,at,as} \times N_{spf,en,ac,at,as} \times \left(AF_{1,en,ac,at,as} \times \ldots \times AF_{m,en,ac,at,as}\right) \quad (6)$$

$$N_{p,en,ac,mv,as} = \min\left[N_{p,en,ac,at,as}, N'_{p,en,ac,mv,as}\right] \quad (7)$$

$$N'_{p,en,ac,mv,as} = C_{en,ac,mv,as} \times N_{spf,en,ac,mv,as} \times \left(AF_{1,en,ac,mv,as} \times \ldots \times AF_{m,en,ac,mv,as}\right) \quad (8)$$

$$N_{p,en,ac,sv,as} = N_{p,en,ac,at,as} - N_{p,en,ac,mv,as} \quad (9)$$

where

$N_{p,en,ac,y,as}$ = predicted average crash frequency of a ramp entrance speed-change lane site on a freeway with any cross section *ac*, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$N'_{p,en,ac,mv,as}$ = unadjusted predicted average crash frequency of a ramp entrance speed-change lane site with any cross section *ac*, multiple-vehicle crash type *mv*, and all severities *as* (crashes/yr);

$N_{spf,en,ac,y,as}$ = predicted average crash frequency of a ramp entrance speed-change lane site on a freeway with base conditions, any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$AF_{m,w,ac,y,as}$ = adjustment factor for feature *m* at site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*; and

$C_{en,ac,y,as}$ = calibration factor for ramp entrance speed-change lanes with any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*.

Equation 7 shows that the multiple-vehicle crash frequency is computed as the smaller of the computed total crash frequency $N_{p,en,ac,at,as}$ and the unadjusted multiple-vehicle crash frequency $N'_{p,en,ac,mv,as}$. By definition, the multiple-vehicle crash frequency cannot exceed the total crash frequency. However, this relationship may not hold for some conditions because the underlying models are based on a regression analysis of observed crash data. For these relatively rare conditions, the single-vehicle crash frequency is implied to be very small and is assumed to equal 0.0 crashes per year.

The predictive model for ramp exit speed-change lane sites is the same as for ramp entrance speed-change lane sites except that the subscript "*ex*" is substituted for "*en*" in each variable.

2.5 PREDICTIVE METHOD FOR FREEWAYS WITH HOV OR HOT LANES

This section describes the predictive method for freeways with HO lanes. It consists of two sections. The first section provides a step-by-step description of the predictive method. The second section describes the geometric design features, traffic control features, and traffic volume data needed to apply the predictive method.

2.5.1 Step-by-Step Description of the Predictive Method

The predictive method for freeways with HO lanes is shown in Figure 1. The project limits are identified, site boundaries established, and site data assembled in Steps 1 to 6. The predictive models are applied to all sites in Steps 7 to 12. If desired, the EB method is applied in Steps 13 to 15. Step 16 summarizes the results for the facility. These steps can be repeated for each design alternative being considered. The information needed to apply each step is provided in this section.

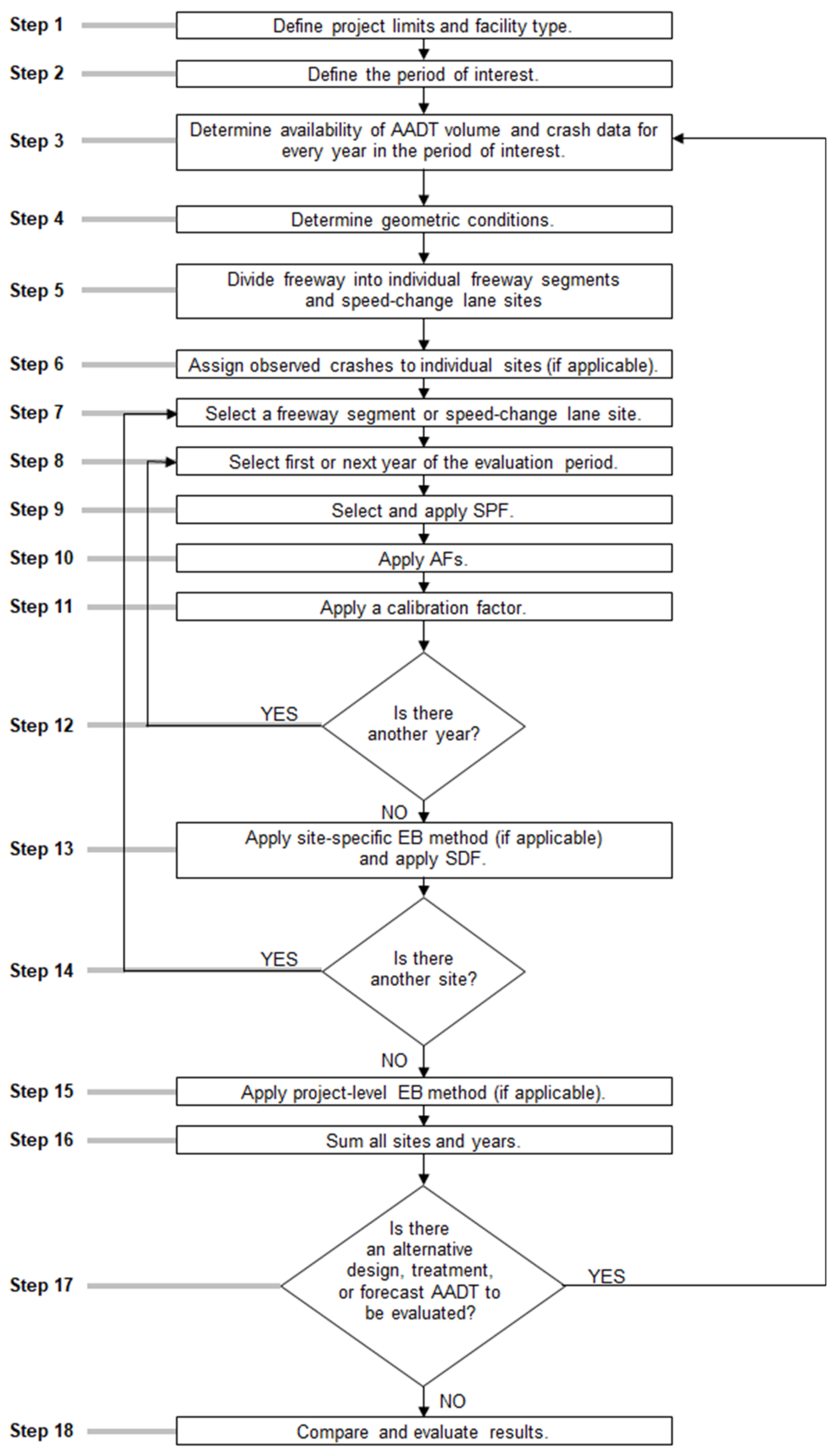


Figure 1. The HSM predictive method.

Step 1—Define the limits of the project.
A project can be a freeway network, a freeway facility, or a site. A site is either a speed-change lane or a freeway segment. Both site types represent one direction of travel. Section 2.4.1 defines freeway segments and speed-change lane sites.

The project limits are defined in this step. They will depend on the purpose of the study. The study may be limited to one specific site or to a group of contiguous sites. Alternatively, the limits can be expanded to include a very long corridor for the purposes of network screening (as discussed in Chapter 4 of the HSM (*4*)). For comparative analysis of design alternatives, the project limits should be the same for all alternatives.

The analyst should identify (or establish) a reference line for the freeway in the subject direction of travel. For this predictive method, the *reference line* is defined as the inner edge line of the inside GP through lane for the subject direction of travel, where the *inner edge line* is the line separating the inside GP through lane and one of the following cross section elements: (a) the HO lane if lane line separation is used, (b) the buffer if buffer separation is used, or (c) the pavement supporting the barrier if barrier separation is used. The location of the reference line is shown in subsequent figures (e.g., Figure 4). Locations along the reference line are specified using a linear referencing system, and are identified using the label "milepost *X*," where the number for *X* has units of miles (e.g., milepost 1.4).

Step 2—Define the period of interest.
The *study period* is defined as the consecutive years for which an estimate of the average crash frequency is desired. The *crash period* is defined as the consecutive years for which observed crash data are available. The *evaluation period* is defined as the combined set of years represented by the study period and crash period. Every year in the evaluation period is evaluated using the predictive method. All periods are measured in years.

If the EB Method is not used, then the study period is the same as the evaluation period. The EB Method is discussed in more detail in Step 3.

If the EB Method is used and the crash period is not fully included in the study period, then the predictive models need to be applied to the study years *plus* each year of the crash period not represented in the study period. In this situation, the evaluation period includes the study period and any additional years represented by the crash data but not in the study period. For example, let the study period be defined as the years 2010, 2011, and 2012. If crash data are available for 2008, 2009, and 2010, then the evaluation period is 2008, 2009, 2010, 2011, and 2012.

The study period can represent either a past time period or a future time period. Whether the predictive method is used for a past or future period depends upon the purpose of the study. The study period may be:

- A past period for:
  - An existing freeway network, facility, or site. If observed crash data are available, the study period is the period of time for which the observed crash data are available and the site geometric design features, traffic control features, and traffic volumes are known.

  - An existing freeway network, facility, or site for which alternative geometric design or traffic control features are proposed (for near-term conditions) and site traffic volumes are known.
- A future period for:
  - An existing freeway network, facility, or site for a future period where forecast traffic volumes are available.
  - An existing freeway network, facility, or site for which alternative geometric design or traffic control features are proposed and forecast traffic volumes are available.
  - A new freeway network, facility, or site that does not currently exist but is proposed for construction and for which forecast traffic volumes are available.

Step 3—For the period of interest, determine the availability of AADT volume and crash data.

Traffic volume data are acquired in this step. Also, a decision is made whether the EB Method will be applied. If it will be applied, then it must also be decided whether the site-specific or project-level EB Method will be applied. If the EB Method will be applied, then the observed crash data are also acquired in this step.

Determining Traffic Volumes

The SPFs used in Step 9 include annual average daily traffic (AADT) volume as a variable. For a past period, the AADT volume may be determined by using automated recorder data or estimated by a sample survey. For a future period, the AADT volume may be a forecast estimate based on appropriate land use planning and traffic volume forecasting models.

For each freeway segment, the AADT volume of the freeway segment is required. For each speed-change lane site, two values are required: (a) the AADT volume of the freeway segment and (b) the AADT volume of the ramp.

The AADT volumes are needed for each year of the evaluation period. The AADT volume for a given year represents an annual average daily 24-hour traffic volume. The freeway segment AADT volume is a one-way volume (i.e., the volume in the subject travel direction).

In many cases, it is expected that AADT data will not be available for all years of the evaluation period. In that case, an estimate of AADT volume for each missing year is interpolated or extrapolated, as appropriate. If there is not an established procedure for doing this, the following rules may be applied within the predictive method to estimate the AADT volumes for years when such data are not available. If these rules are applied, the fact that some AADT volumes are estimated should be documented with the analysis results.

- If AADT volume is available for only a single year, that same volume is assumed to apply to all years of the evaluation period.
- If two or more years of AADT data are available, the AADT volumes for intervening years are computed by interpolation.
- The AADT volumes for years before the first year for which data are available are assumed to be equal to the AADT volume for that first year.

- The AADT volumes for years after the last year for which data are available are assumed to be equal to the AADT volume for that last year.

Determining Availability of Observed Crash Data

Where an existing site (or an alternative condition for an existing site) is being considered, the EB Method can be used to obtain a more reliable estimate of the average crash frequency. The EB Method is applicable when crash data are available for the entire project, or for its individual sites. Crash data may be obtained directly from the jurisdiction's crash report system. At least two years of crash data are desirable to apply the EB Method. The EB Method (and criteria to determine whether the EB Method is applicable) is presented in the appendix for Part C of the HSM (*4*).

The EB Method can be applied at the site-specific level or at the project level. At the site-specific level, crash data are assigned to specific sites in Step 6. The site-specific EB Method is applied in Step 13. At the project level, crash data are assigned to a group of sites (typically because they cannot be assigned to individual sites). The project-level EB Method is applied in Step 15. The site-specific EB Method will provide the best results if crash data can be accurately assigned to the sites. Guidance to determine whether the site-specific or project-level EB Method is applicable is presented in the appendix for Part C of the HSM (*4*).

Step 4—Determine geometric design features, traffic control features, and site characteristics for all sites in the project limits.

A range of data is needed to apply a predictive model. These data are used in the SPFs and AFs to estimate the predicted average crash frequency for the selected site and year. These data represent the geometric design features, traffic control features, and traffic demand characteristics that have been found to have some relationship to crash potential. These data are needed for each site in the project limits. They are needed for the study period and, if applicable, the crash period. These data, and the means by which they are measured or obtained, are described in Section 2.5.2.

Step 5—Divide the freeway into sites.

Divide the freeway into individual sites (i.e., freeway segments and speed-change lanes) using the information from Step 1 and Step 4. The procedure for dividing the freeway into individual sites is provided in Section 2.6.

Step 6—Assign observed crashes to the individual sites (if applicable).

Step 6 applies if it was determined in Step 3 that the site-specific EB Method is applicable. If the site-specific EB Method is not applicable, then proceed to Step 7. In this step, the observed crash data are assigned to the individual sites. Guidance for assigning crashes to individual sites is outlined in Section 2.6.3.

Step 7—Select the first or next individual site in the project limits. If there are no more sites to be evaluated, proceed to Step 15.
Steps 7 through 14 are repeated for each site within the project limits. Any site can be selected for evaluation because each site is considered to be independent of the other sites. However, good practice is to select the sites in an orderly manner, such as in the order of their physical occurrence in the subject direction of travel.

Step 8—For the selected site, select the first or next year in the period of interest. If there are no more years to be evaluated for that site, proceed to Step 13.
Steps 8 through 12 are repeated for each year in the evaluation period for the selected site. The individual years of the evaluation period are analyzed one year at a time because the SPFs and some AFs are dependent on AADT volume, which may change from year to year.

Step 9—For the selected site, determine and apply the appropriate SPF.
The SPF determines the predicted average crash frequency for a site with features that match the SPF's base conditions. The SPFs (and their base conditions) are described in Sections 2.7.1 and 2.8.1.

Determine the appropriate SPF for the selected site based on its site type and cross section. This SPF is then used to compute the crash frequency for the selected year using the AADT volume for that year, as determined in Step 3.

Step 10—Multiply the result obtained in Step 9 by the appropriate AFs.
Collectively, the AFs are used in the predictive model to adjust the SPF estimate from Step 9 so that the resulting predicted average crash frequency accurately reflects the geometric design and traffic control features of the selected site. The available AFs are described in Sections 2.7.2 and 2.8.2.

All AFs presented in this chapter have the same base conditions as the SPFs in this chapter. Only the AFs presented in Sections 2.7.2 and 2.8.2 may be used as part of the predictive method described in this chapter.

For the selected site, determine the appropriate AFs for the site type, geometric design features, and traffic control features present. The AF's designation by crash type must match that of the SPF with which it is used (unless indicated otherwise in the AF description). The AFs for the selected site are calculated using the geometric design and traffic control features determined in Step 4.

Multiply the result from Step 9 by the appropriate AFs.

Step 11—Multiply the result obtained in Step 10 by the appropriate calibration factor.
The SPFs and AFs in this chapter have each been developed with data from specific jurisdictions and time periods. Calibration to local conditions will account for any differences between these conditions and those present at the selected sites. A calibration factor is applied to each SPF in the predictive method. Detailed guidance for the development of calibration factors is included in the appendix for Part C of the HSM (*4*).

Multiply the result from Step 10 by the calibration factor to obtain the predicted average crash frequency.

Step 12—If there is another year to be evaluated in the evaluation period for the selected site, return to Step 8. Otherwise, proceed to Step 13.
This step creates a loop from Step 8 through Step 12 that is repeated for each year of the evaluation period for the selected site.

Step 13—Apply the site-specific EB Method (if applicable) and apply crash distributions.
The site-specific EB Method combines the *predicted* average crash frequency computed in Step 11 with the observed crash frequency of the selected site to produce an estimate of the *expected* average crash frequency. The expected average crash frequency is more statistically reliable than the predicted average crash frequency obtained in Step 11. The procedure for applying the site-specific EB Method is provided in the appendix for Part C of the HSM (*4*).

If the EB Method is used, then an estimate of expected average crash frequency is obtained for each year of the crash period (i.e., the period for which the observed crash data are available). The individual years of the crash period are analyzed one year at a time because the SPFs and SDFs are dependent on AADT volume, which may change from year to year.

Apply the site-specific EB Method to a future time period, if appropriate.

The appendix for Part C of the HSM (*4*) provides a procedure for converting the estimates from the EB Method to any years in the study period that are not represented in the crash period (e.g., future years). This approach gives consideration to any differences in traffic volume, geometry, or traffic control between the study period and the crash period. This procedure yields the expected average crash frequency for each year of the study period.

Apply the severity distribution, if desired.

The severity distribution function (SDF) is used to compute the average crash frequency for each of the following severity levels: fatal *K*, incapacitating injury *A*, non-incapacitating injury *B*, possible injury *C*, and property-damage-only *PDO*. An SDF is used to compute the severity distribution proportions. Each SDF includes variables that describe the geometric design and traffic control features of a site. In this manner, the computed distribution gives consideration to the features present at the selected site. The SDFs are described in Sections 2.7.3 and 2.8.3. They can benefit from being calibrated to local conditions as part of the calibration process. Detailed guidance for the development of the SDF calibration factor is included in the appendix for Part C of the HSM (*4*).

Apply the crash type distribution, if desired.

Each predictive model includes a default distribution of crash type. These distributions can be used to compute the average crash frequency for each of ten crash types (e.g., head-on, fixed object). The distributions are presented in Sections 2.7.4 and 2.8.4. The distributions can provide a more reliable indication of local crash characteristics if they are updated based on local data as part of the calibration process.

Step 14—If there is another site to be evaluated, return to Step 7; otherwise, proceed to Step 15.
This step creates a loop from Step 7 through Step 14 that is repeated for each site of interest.

Step 15—Apply the project-level EB Method (if applicable) and apply crash distributions.
The activities undertaken during this step are the same as undertaken for Step 13 but they occur at the project level (i.e., network or facility). They are based on estimating the project-level predicted average crash frequency. This crash frequency is computed for each year during the crash period. It is computed as the sum of the predicted average crash frequency for all sites (as computed in Step 11).

The project-level EB Method combines the project-level *predicted* average crash frequency with the observed crash frequency for all sites within the project limits to produce an estimate of the project-level *expected* average crash frequency. The project-level expected average crash frequency is more statistically reliable than the project-level predicted average crash frequency. The procedure for applying the project-level EB Method is provided in the appendix for Part C of the HSM (*4*).

If the EB Method is used, then an estimate of the project-level expected crash frequency is obtained for each year of the crash period (i.e., the period for which the observed crash data are available). The individual years of the crash period are analyzed one year at a time because the SPFs and SDFs are dependent on AADT volume, which may change from year to year.

Apply the project-level EB Method to a future time period, if appropriate.

Follow the same guidance as provided in Step 13 using the estimate from the project-level EB Method.

Apply the severity distribution, if desired.

Follow the same guidance as provided in Step 13 using the estimate from the project-level EB Method.

Apply the crash type distribution, if desired.

Follow the same guidance as provided in Step 13 using the estimate from the project-level EB Method.

Step 16—Sum all sites and years in the study to estimate the total crash frequency.
One outcome of the predictive method is the total (predicted or expected) average crash frequency. The term "total" indicates that the estimate includes all crash types and severities. It is computed from an estimate of the total number of crashes, which represents the sum of the total average crash frequency for each site and for each year in the study period. The total *expected* number of crashes during the study period is calculated using Equation 10. The same equation can be used to calculate the total *predicted* number of crashes by substituting the subscript "*p*" for the subscript "*e*".

$$N^{*}_{e,aS,ac,at,as} = \sum_{j=1}^{n_s}\left(\sum_{i=1}^{\text{all sites}} N_{e,fs(i),n,at,as,j} + \sum_{i=1}^{\text{all sites}} N_{e,en(i),ac,at,as,j} + \sum_{i=1}^{\text{all sites}} N_{e,ex(i),ac,at,as,j}\right) \quad (10)$$

where

$N^*_{e,aS,ac,at,as}$ = total expected number of crashes for all sites *aS* and all years in the study period (includes all cross sections *ac*, all crash types *at*, and all severities *as*) (crashes);

n_s = number of years in the study period (yr);

$N_{e,fs(i),n,at,as,j}$ = expected average crash frequency of freeway segment *i* with *n* lanes for year *j* (includes all crash types *at* and all severities *as*) (crashes/yr); and

$N_{e,w(i),ac,at,as,j}$ = expected average crash frequency of speed-change lane site *i* of type *w* (*w* = *en*: ramp entrance speed-change lane; *ex*: ramp exit speed-change lane) with any cross section *ac* for year *j* (includes all crash types *at* and all severities *as*) (crashes/yr).

Equation 10 is used to compute the total expected number of crashes estimated to occur in the project limits during the study period.

Equation 11 is used to estimate the overall expected average crash frequency within the project limits during the study period. The same equation can be used to calculate the total *predicted* number of crashes by substituting the subscript "*p*" for the subscript "*e*".

$$N_{e,aS,ac,at,as} = \frac{N^*_{e,aS,ac,at,as}}{n_s} \quad (11)$$

where

$N_{e,aS,ac,at,as}$ = overall expected average crash frequency for all sites *aS* and all years in the study period (includes all cross sections *ac*, all crash types *at*, and all severities *as*) (crashes/yr).

Step 17—Determine if there is an alternative design, treatment, or forecast AADT to be evaluated.

Steps 3 through 17 are repeated as appropriate for the same project limits but for alternative conditions, treatments, periods of interest, or forecast AADT volumes.

Step 18—Evaluate and compare results.

The crash frequency estimates obtained from the previous steps represent statistically reliable estimates of the (expected or predicted) average crash frequency for each configuration (e.g., existing condition, alternative design) that is evaluated. The estimates are based on the configuration's specified project limits, study period, geometric design, traffic control features, and AADT volume. The estimates can be used to assess the safety associated with each site and the overall project based on consideration of crash type and severity. The estimates can be used to identify treatments or design changes that have the potential for reducing crash frequency, severity, or both. The estimates can also be used to compare the relative safety of alternative designs.

2.5.2 Data Needed to Apply the Predictive Method

The input data needed for the predictive models are identified in this section. These data represent the geometric design features, traffic control features, and traffic demand characteristics that have been found to have some relationship to crash potential. The input data are needed for each one-directional site of interest in the project limits. Criteria for defining site boundaries are described in Section 2.6.

There are several data elements identified in this section that describe a length along the roadway (e.g., segment length, curve length, etc.). All of these lengths are measured along the reference line established in Step 1 of the predictive method. Points that do not lie on the reference line must be projected onto the reference line (along a perpendicular line if the alignment is straight, or along a radial line if the alignment is curved) to facilitate length determination. These dimensions can be obtained from field measurements, a plan set, or aerial photographs.

The input data needed for the predictive models include the following:

- *Number of GP through lanes*—For a freeway segment, use the total number of GP through lanes in the subject direction of travel. For a speed-change lane site, use the number of GP through lanes in the portion of freeway adjacent to the speed-change lane. The predictive models are limited to freeways with two to seven GP through lanes. A segment with a lane-add (or lane-drop) taper is considered to have the same number of through lanes as the roadway just downstream of the lane-add (or lane-drop) taper. This guidance is shown in Figure 2. The definition of "GP through lane" is provided in Section 2.4.1.

  Do not include any HOV, HOT, or other managed lanes.

  Do not include any auxiliary lanes that are associated with a weaving section, unless the weaving section length exceeds 0.85 mi (4,500 ft). If this length is exceeded, then the auxiliary lane is counted as a GP through lane that starts as a lane-add ramp entrance and ends as a lane-drop ramp exit.

  Do not include the speed-change lane that is associated with a ramp that merges with (or diverges from) the freeway, unless its length exceeds 0.30 mi (1,600 ft). If this length is exceeded, then the speed-change lane is counted as a GP through lane that starts as a lane-add ramp entrance and ends as a lane drop by taper (or starts as a lane add by taper and ends as a lane-drop ramp exit).

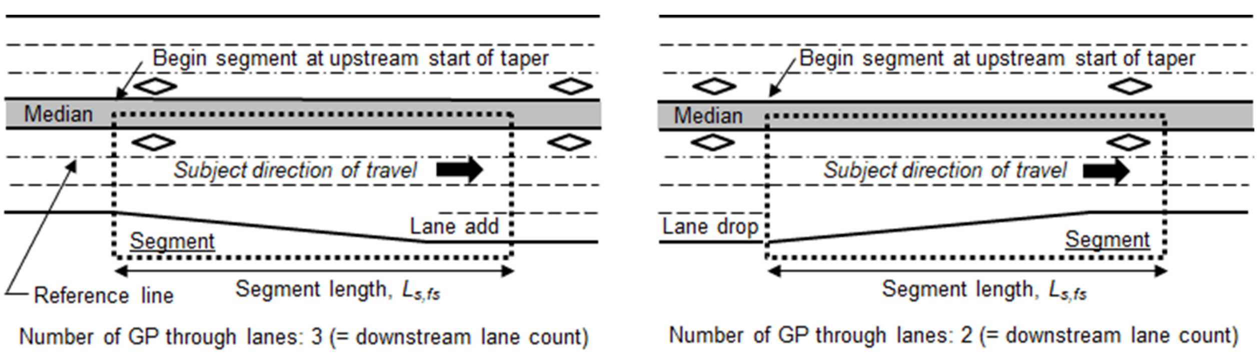


Figure 2. Through-lane count in segments with lane add or lane drop.

- *Number of HO lanes (at speed-change lane sites)*—The number of HO lanes in the portion of freeway adjacent to the speed-change lane. The predictive models are limited to freeways with one to four HO lanes. The definition of "HO lane" is provided in Section 2.4.1.

- *Length of freeway segment, length of speed-change lane site, and length of speed-change lane (if present)*—As discussed in Section 2.4.1, a speed-change lane site has a length that is less than or equal to that of the associated speed-change lane. The speed-change lane length is measured from the gore point to the taper point. Figure 3 illustrates these measurement points for a ramp entrance and a ramp exit speed-change lane with the parallel and taper design, respectively.

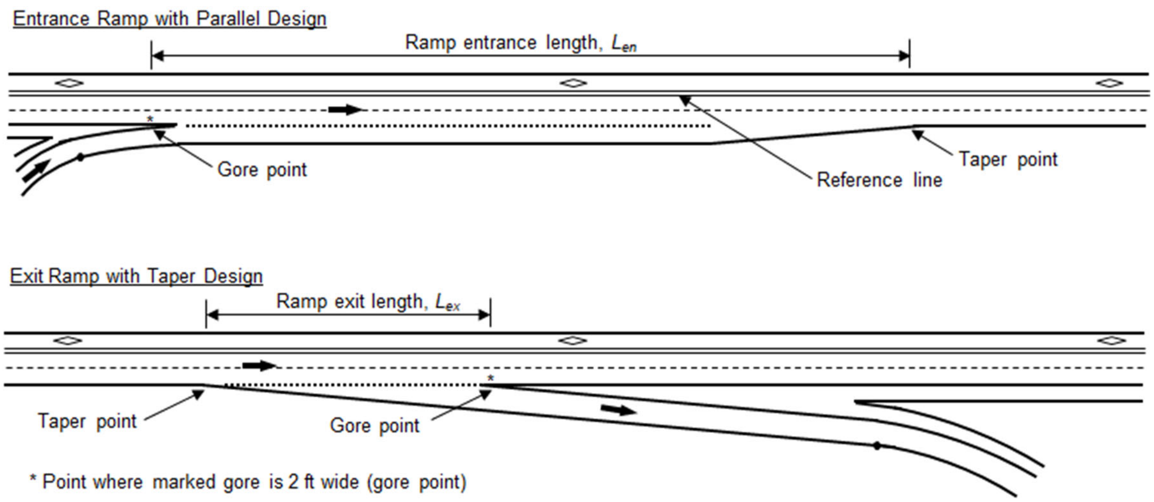


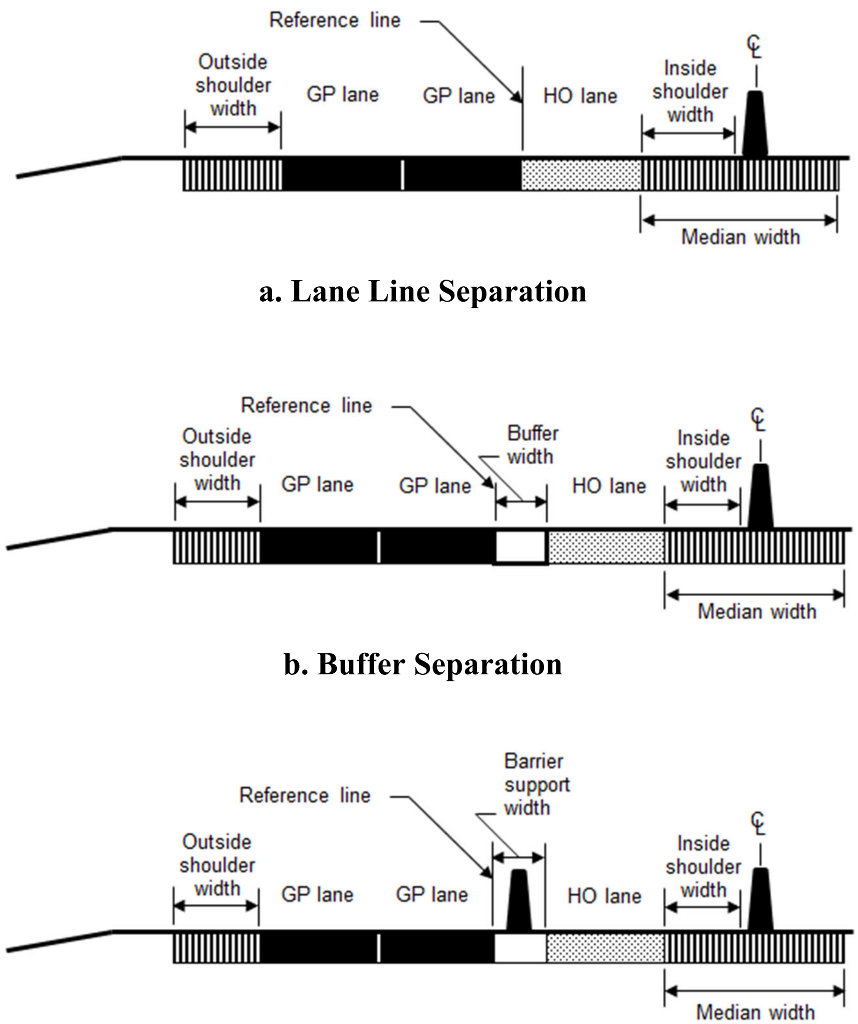
Figure 3. Freeway speed-change lane length.

The gore point is located where the pair of solid white pavement edge markings that separate the ramp from the freeway main lanes are 2.0 ft apart (as shown in Figure 3). If the markings do not extend to a point where they are 2.0 ft apart, then the gore point is found by extrapolating both markings until the extrapolated portion is 2.0 ft apart.

- *Presence of horizontal curve*—If a curve is present, then the two data elements described in the following list are needed.
  - *Length of curve*—Curve length is measured along the reference line from the point where the tangent ends and the curve begins (i.e., the PC) to the point where the curve ends and the tangent begins (PT). If the curve PC and PT do not lie on the reference line, then they must be projected onto this line and the curve length measured between these projected points along the reference line.

    If the curve has spiral transitions, then measure from the "effective" PC point to the "effective" PT point. The effective PC point is located midway between the TS and SC, where the TS is the point of change from tangent to spiral and the SC is the point of change from spiral to circular curve. The effective PT is located midway between the CS and ST, where CS is the point of change from circular curve to spiral and ST is the point of change from spiral to tangent.
  - *Length of curve in site*—The length of the curve within the boundaries of the site (i.e., segment or speed-change lane). This length cannot exceed the site length or the curve length.

- *Speed limit*—Regulatory speed limit for passenger cars traveling on the freeway in the subject direction of travel. Based on the posted speed limit sign at the site (or just upstream of the site if a sign is not present at the site).
- *Width of buffer, outside shoulder, inside shoulder, and median*—The values assigned to these data elements should be representative of the overall site. They are shown in Figure 4 for three types of lateral separation.



a. Lane Line Separation

b. Buffer Separation

c. Barrier Separation

Figure 4. Measurement of cross section data elements.

These cross section data elements should not be measured where one or more edges are discontinuous or tapered. Rather, they should be measured where the cross section is constant, such as along line A or B in Figure 5. If a width varies along the segment or speed-change lane site (but not enough to justify beginning a new site), then compute the length-weighted average width.

- *Buffer width*—This width is needed only if the lateral separation type is “flush buffer.”
- *Shoulder width*—This width represents only the paved width.
- *Median width*—This width is measured between the edges of the traveled way for the two roadways serving opposing directions of travel. The median width includes the width of the inside shoulders that are present in the subject and opposing travel directions. The median width does *not* include the width of the HO lane(s), buffer width, or the barrier support width between the GP lane and the HO lane.

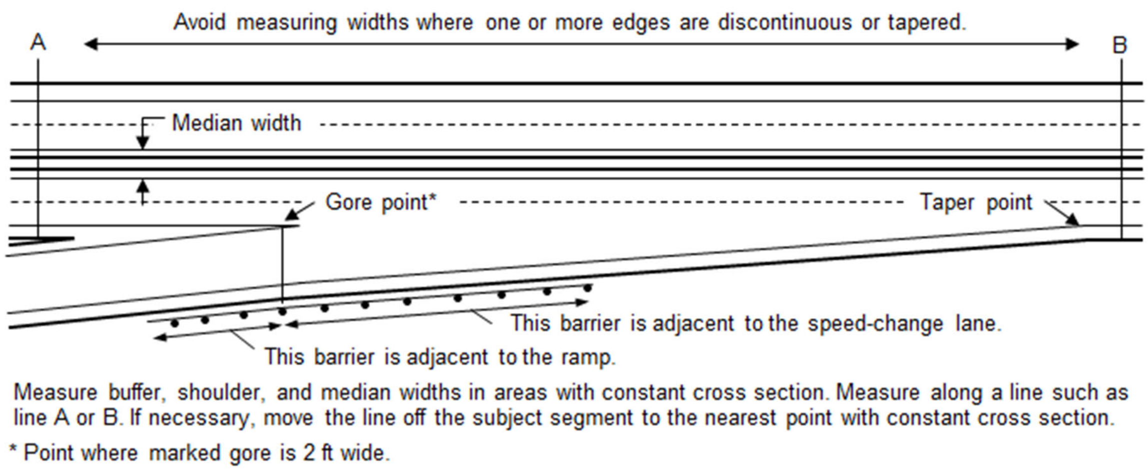


Figure 5. Measurement of cross section data elements near a speed-change lane.

- *Length of the barrier in the median and the barrier on the roadside*—This length is measured for each piece of barrier “associated” with the subject site (i.e., freeway segment or speed-change lane). A barrier is associated with the site if its offset from the near edge of traveled way is 30 ft or less. Barrier adjacent to a ramp (as shown in Figure 5) but also within 30 ft of the freeway traveled way should also be associated with the subject site.

  Each piece of barrier is represented once for a site. Barrier length is measured along the reference line.
- *Presence of a one-sided Type C weaving section*—This weaving section has the following characteristics: (a) one of the two weaving movements can be made without making any lane changes, (b) the other weaving movement requires two or more lane changes, and (c) the ramp entrance and ramp exit associated with the weaving section are located on the right side of the freeway. The typical one-sided Type C weaving section is shown in Figure 6.

  If the subject freeway travel direction has the aforementioned characteristics within a length of 0.85 mi (4,500ft) or less, then a one-sided Type C weaving section is consider to be present. This length is measured along the edge of the freeway traveled way from the gore point of the ramp entrance to the gore point of the next ramp exit, as shown in Figure 6. If the measured gore-to-gore distance exceeds 0.85 mi (4,500 ft), then a weaving section is not considered to exist. Rather, the entrance ramp is a "lane add" and the exit ramp is a "lane drop."

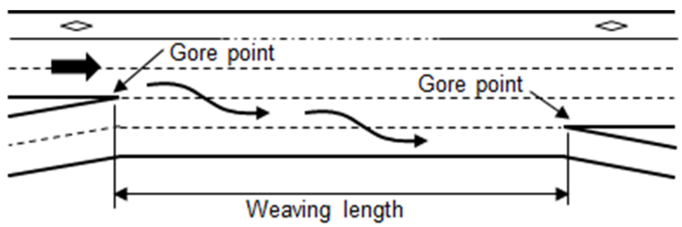
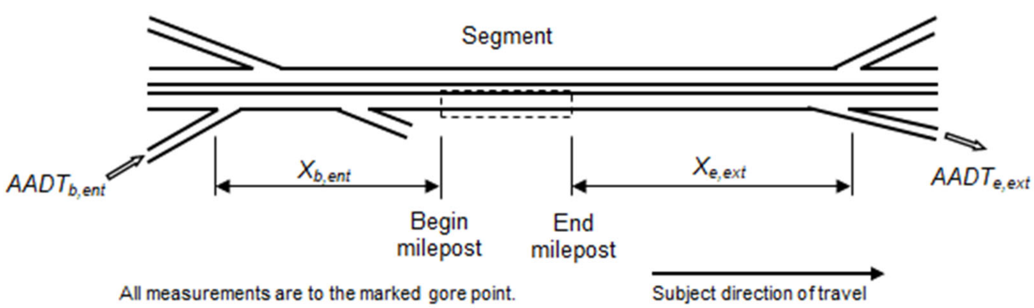


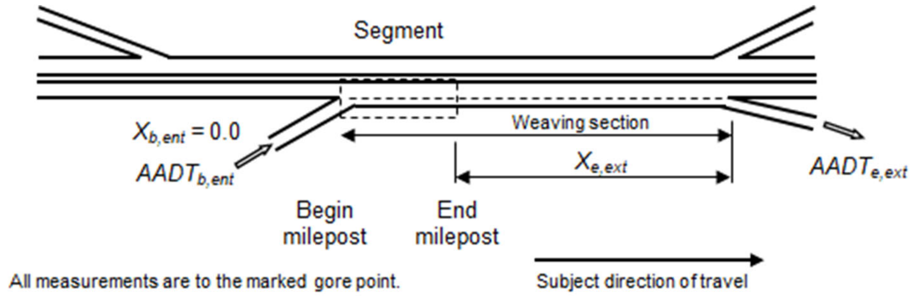
Figure 6. One-sided Type C weaving section.

- *Distance to nearest upstream entrance ramp*—The value assigned to this data element represents the distance from the segment boundary to the ramp gore point, as measured along the reference line. The distance to the nearest upstream entrance ramp is shown in Figure 7 using the variable $X_{b,ent}$. If the ramp entrance is located at the start of the subject segment (as in Figure 7b), then the corresponding distance is equal to 0.0 mi. If the ramp does not exist or it is located more than 2.0 mi from the segment, then this distance can be set to 2.0 mi in the predictive method to obtain the correct results.

  Figure 7a shows a freeway segment with an upstream exit ramp serving travel in the subject direction of travel. Upstream exit ramps are not of interest to the evaluation of the subject segment and data are not needed for them if they exist in the vicinity of the segment.



a. All Ramps External to the Segment



b. Three Ramps External to the Segment and One Ramp in the Segment

Figure 7. Distance to nearest ramp.

- *Distance to nearest downstream exit ramp*—The measurement technique and maximum value for this data element is the same as for upstream entrance ramps. This distance is shown in Figure 7 using the variable $X_{e,ext}$. Downstream entrance ramps are not of direct interest, and their data are not needed.
- *Proportion of hours in the average day where the lane volume exceeds 1,000 vehicles per hour per lane (veh/h/ln)*—The lane volume for hour *i* (LV_i) is computed as $LV_i = HV_i/n_{GPL}$ where HV_i is the volume during hour *i* (*i* = 1, 2, 3, ... , 24) and n_{GPL} is the number of GP through lanes. The desired proportion P_{hvh} is computed as $P_{hvh} = (\Sigma\, m)/24$ where $\Sigma\, m$ is the count of hours where the lane volume exceeds 1,000 veh/h/ln. The *HV* and n_{GPL} variables represent the subject travel direction (i.e., they are one-directional values). These data will typically be obtained from the continuous traffic counting station that (a) is nearest to the subject freeway and (b) has similar traffic demand and peaking characteristics. A default value can be computed using the following equation.

$$P_{hvh} = \frac{\exp\left[-1.441 + 0.03766 \times \frac{AADT}{1000 \times n_{GPL}}\right]}{1 + \exp\left[-1.441 + 0.03766 \times \frac{AADT}{1000 \times n_{GPL}}\right]} \quad (12)$$

where

P_{hvh} = proportion of hours where volume exceeds 1,000 veh/h/ln;

$AADT$ = AADT volume of freeway in the subject travel direction, veh/day; and

n_{GPL} = number of GP through lanes in the subject travel direction (lanes).

- *Freeway AADT volume*—The freeway AADT volume describes the annual average daily traffic volume the subject travel direction (i.e., it is a one-directional value). If a one-directional AADT is not available, it can be estimated as one-half of the two-directional value. This volume includes vehicles using the HO lane(s) and the GP lanes.
- *Entrance ramp AADT volume, Exit ramp AADT volume*—The annual average daily traffic volume of the ramp. This volume includes vehicles using the GP lanes and the HO bypass lane (if present) on the ramp. The evaluation of a freeway segment requires the nearest upstream entrance ramp AADT volume (if within 2.0 miles of the segment) and the nearest downstream exit ramp volume (if within 2.0 miles of the segment). The evaluation of a ramp entrance speed-change lane requires the entrance ramp AADT

volume and the nearest downstream exit ramp volume (if within 2.0 miles of the site). The evaluation of a ramp exit speed-change lane requires the exit ramp AADT volume and the nearest upstream entrance ramp volume (if within 2.0 miles of the site).

- *HO lane access restriction by time of day*—A through lane may operate as a *part-time HO lane* or a *full-time HO lane*. A part-time HO lane operates as an HO lane during specific times of day (e.g., peak hours) and as a GP lane during the other hours of the day. In contrast, a full-time HO lane operates as an HO lane throughout the day (i.e., it operates as an HO lane during all 24 hours of the day). This data element is used to indicate whether the subject site has a part-time HO lane or a full-time HO lane.
- *Distance from the last HO lane egress point to the next exit ramp*—The value assigned to this data element represents the distance between the last egress point of the HO lane and the gore point of the next exit ramp. This distance is measured along the reference line. It is shown in Figure 8 using the variable X_{DA}. This variable is required when the HO lane has at-grade entrance and exit zones and the subject site begins and ends within the distance X_{DA} [i.e., it is not needed if (a) the HO lane has continuous access, (b) the site ends before or at the egress point, or (c) the site starts at or after the gore point].

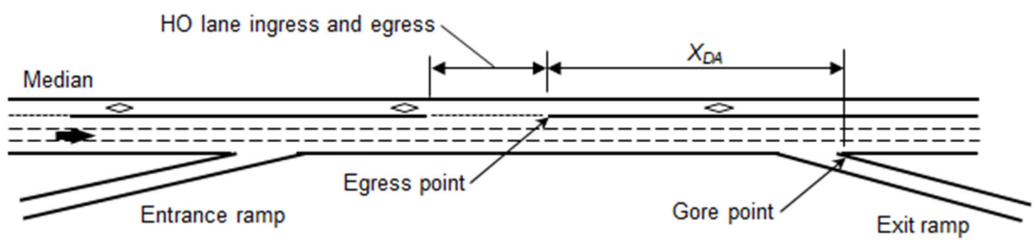


Figure 8. Distance from HO lane egress point to exit ramp.

- *Average speed differential between the inside GP lane and the HO lane(s)*—This average is computed using the measured spot speed of the motorized vehicle traffic stream in the inside GP lane and in the HO lane(s). For a given month *i*, the speed of each vehicle using a lane of interest is measured. These speeds are then averaged for the GP lane and for the HO lane(s). Their difference ($\Delta_{v,i} = Speed_{HO,i} - Speed_{GP,i}$) is computed for month *i*. This process is repeated for all months of the year. The 12 monthly speed differences are then averaged for the year of interest and, if this annual average difference is negative, it is set to 0.0.

  The speed data used for this calculation can be obtained from the continuous traffic counting station that (a) is nearest to the subject freeway and (b) has similar traffic demand and peaking characteristics. Data for a sample of representative days of the month and months of the year can be used to reduce the amount of data needed for this calculation. A default value can be computed using the following equation.

$$\Delta_v = \max\left[0.0, \quad -0.0038 \times \left(\frac{AADT}{1000 \times n_{GPL}}\right)^2 + 0.2544\left(\frac{AADT}{1000 \times n_{GPL}}\right) - 0.0628\right] \qquad (13)$$

where

Δ_v = average speed differential between the inside GP lane and the HO lane(s) (mi/h);

$AADT$ = one-directional AADT volume of the freeway (including vehicles in the HO lane), veh/day; and

n_{GPL} = number of GP through lanes in the subject travel direction (lanes).

2.6 FREEWAY SEGMENTS AND SPEED-CHANGE LANES WITH HOV OR HOT LANES

This section consists of three subsections. The first subsection describes how the freeway facility is represented as a contiguous set of sites. The second subsection provides guidelines for segmenting the freeway facility. The assignment of crashes to sites is discussed in the last subsection.

2.6.1 Representing the Freeway Facility as a Set of Sites

For analysis purposes, a freeway facility is considered to consist of a contiguous set of freeway segments, ramp entrance speed-change lane sites, and ramp exit speed-change lane sites. These components are generally referred to as "sites." Each site type is defined in Section 2.4.1.

Figure 9 illustrates the three site types in the context of a short length of freeway near an interchange. The figure shows five sites (with grey shading) for the right-to-left direction of travel. Three freeway segments are labeled *Fr1*, *Fr2*, and *Fr3* in the figure. The speed-change lane site associated with the entrance ramp is labeled *SCen* and that associated with the exit ramp exit is labeled *SCex*.

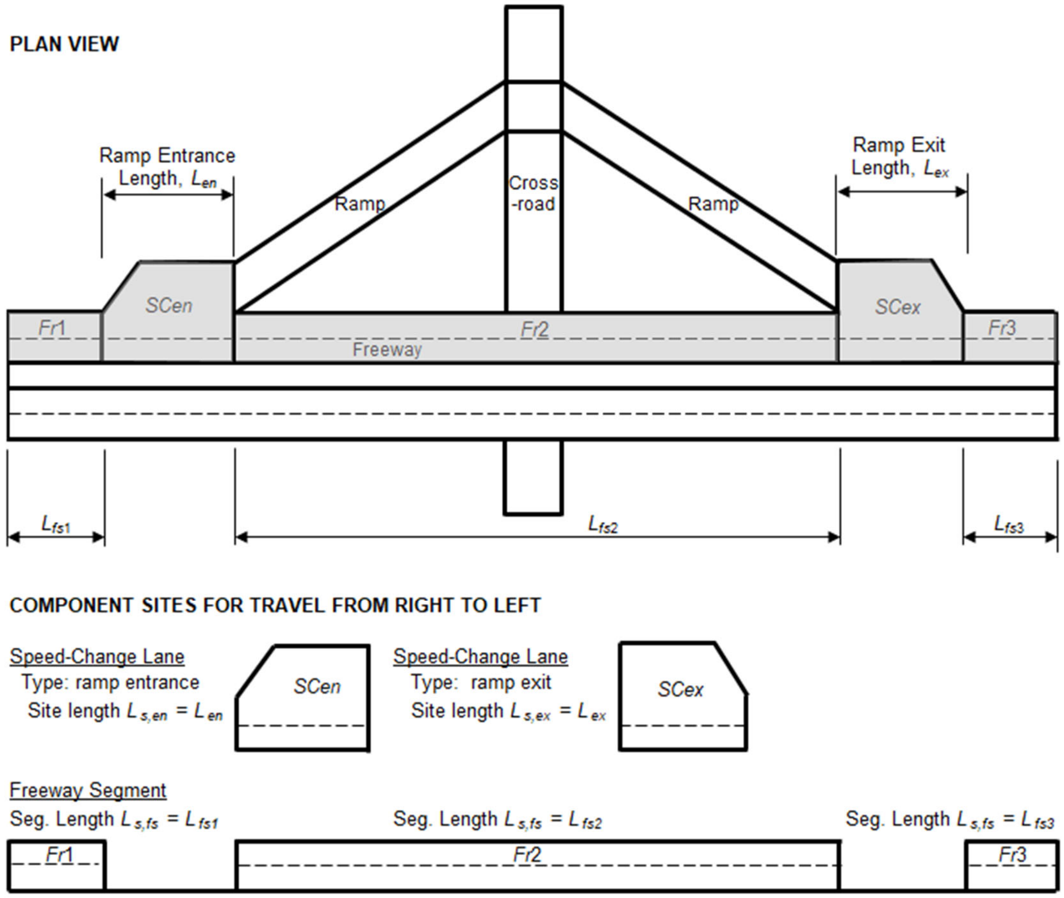


Figure 9. Illustrative sites for one-directional freeway facility evaluation.

The predictive model for speed-change lane sites estimates the average frequency of crashes that are associated with the presence and operation of the speed-change lane. These crashes occur in Region A of Figure 10 (this region is defined by the gore point and the taper point). Crashes that occur outside of Region A (i.e., in Region B) are associated with a freeway segment.

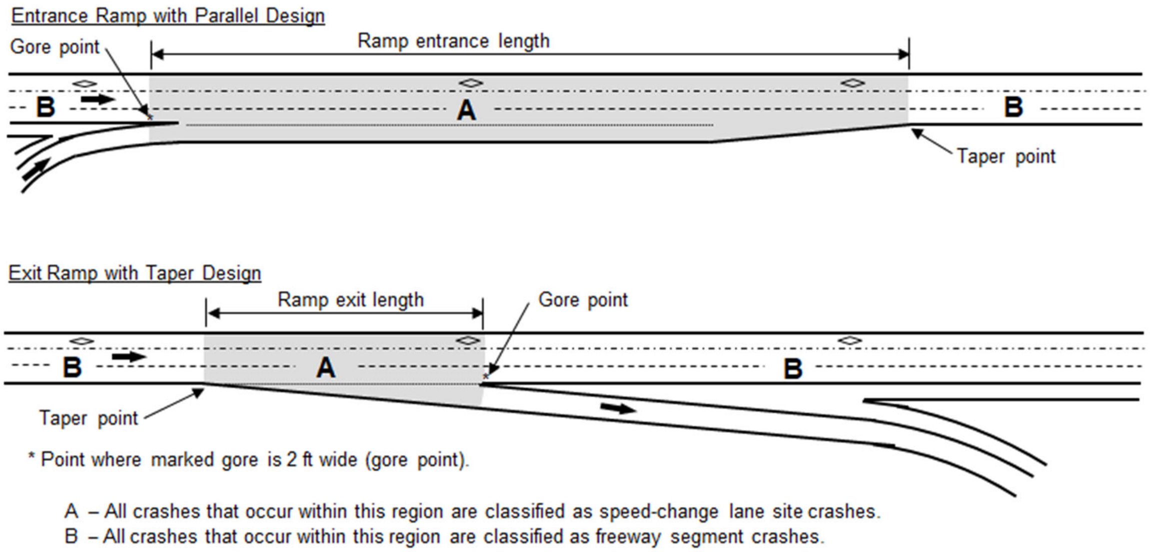


Figure 10. Definition of freeway segment and speed-change lane.

2.6.2 Segmentation Process

As a first step of the segmentation process, the freeway in the subject direction of travel is subdivided into sites. A speed-change lane site begins at the gore (or taper) point and ends at the associated taper (or gore) point. These points are shown in Figure 10. Any site that is not a speed-change lane site is a freeway segment. A freeway segment or a speed-change lane site can be subdivided into two or more sites if dictated by the segmentation guidelines described in subsequent paragraphs.

As a second step of the segmentation process, the sites identified in the first step are further subdivided (if needed) to ensure that they are homogeneous with respect to characteristics such as traffic volume, key geometric design features, and traffic control features. A new site begins where there is a change in at least one of the characteristics identified in the following list. The phrases "GP through lanes" and "HO lane" are defined in Section 2.4.1. The listed characteristics are described in Section 2.5.2.

- *Number of GP through lanes*—Begin a site at the gore point if the GP lane is added or dropped at a ramp. Begin a segment at the upstream start of taper if the GP lane is added or dropped by taper. Guidance in this regard is described in the text accompanying Figure 2.
- *Number of HO lanes*—Begin a site at the gore point if an HOV or HOT lane is added or dropped at a ramp. Begin a site at the upstream start of taper if an HOV or HOT lane is added or dropped by taper.
- *Speed limit*—Begin a site at the point where the posted speed limit sign is located that indicates a change in the regulatory speed limit.
- *Buffer width*—If a flush buffer is used for lateral separation, measure the buffer width at successive points along the roadway. Compute an average buffer width for each point and

round this average to the nearest 0.5 ft. Begin a new site if the rounded value for the current point changes from that of the previous point (e.g., from 3.0 to 3.5 ft).

- *Outside shoulder width*—Measure the outside shoulder width at successive points along the roadway. Compute an average shoulder width for each point and round this average to the nearest 1.0 ft. Begin a new site if the rounded value for the current point changes from that of the previous point (e.g., from 6 to 7 ft).
- *Inside shoulder width*—Measure the inside shoulder width at successive points along the roadway. Compute an average shoulder width for each point and round this average to the nearest 1.0 ft. Begin a new site if the rounded value for the current point changes from that of the previous point (e.g., from 6 to 5 ft).
- *Median width*—Measure the median width at successive points along the roadway. Round the measured median width at each point to the nearest 10 ft. If the rounded value exceeds 90 ft, then set it to 90 ft. Begin a new site if the rounded value for the current point changes from that of the previous point (e.g., from 30 to 20 ft).
- *Ramp presence*—Begin a site at the ramp gore point.
- *Lateral separation*—As shown in Table 1, four types of lateral separation are addressed by the predictive method (i.e., lane line, flush buffer, pylon buffer, and barrier). Begin a site at the point where there is a change in lateral separation type.
- *HO lane access restriction by time of day*—If the HO lane access hours change from part-time to full-time (or vice versa), begin a site at the point where the change occurs.
- *HO lane egress point*—If the HO lane has at-grade entrance and/or exit zones, begin a site at the downstream end of any zone where egress from the HO lane is allowed. Specifically, begin a site at the egress point (as shown in Figure 8).

Application of the "median width" segmentation criterion is shown in Figure 11. The freeway section in this figure is shown to consist of five segments. Segment 1 has a rounded median width of 70 ft. Segment 2 starts where the rounded median width first changes to 80 ft. Segment 3 begins at the point where the rounded median width first changes to 90 ft. Segment 4 begins where the rounded median width first changes to 80 ft. Segment 5 begins where the rounded median width first changes to 70 ft.

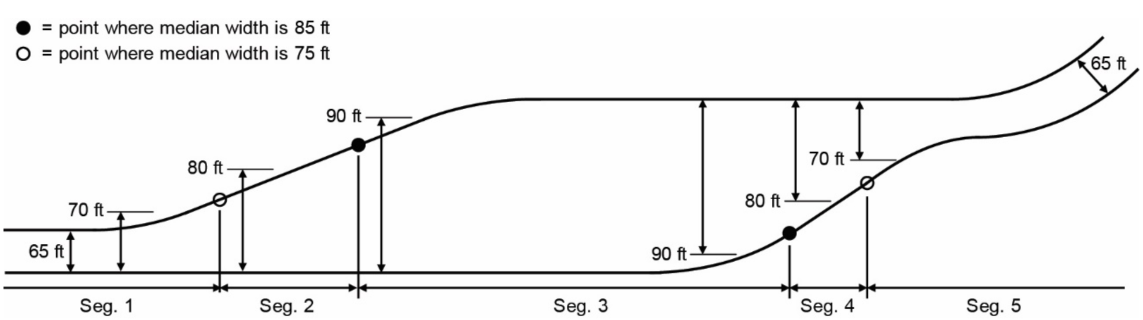


Figure 11. Segmentation for varying median width.

Guidance regarding the location of the buffer, shoulder, and median width measurement points is provided in the text associated with Figure 4 and Figure 5 in Section 2.5.2. Each width represents an average for the site.

The rounded buffer, shoulder, and median width values are used solely to determine site boundaries. Once these boundaries are determined, the unrounded values for the site are then used for all subsequent calculations in the predictive method.

If an alternatives analysis is undertaken, the number (and location) of sites should be the same (or nearly so) for all design configurations being compared. This approach minimizes possible differences in results due to differences in facility segmentation and ensures that the observed differences in results are attributable to design changes. To illustrate this guidance, consider an existing segment that is proposed to have its shoulder width increased by 1.0 foot at its mid-point. The analyst desires to compare the existing and proposed designs to determine the safety effect of the shoulder width increase. The segmentation criteria require the proposed design to be evaluated as two segments (with the end of the first segment and start of the second segment to occur where the shoulder width changes). To ensure that the observed differences in results between the one-segment existing design and two-segment proposed design are attributable to the change in shoulder width, the existing design should also be evaluated as two segments where the first segment ends (and the second segment begins) at the same mid-point location as for the proposed design.

2.6.3 Crash Assignment to Sites

Observed crash counts are needed if the analyst desires to apply the EB method. These crashes are assigned to the individual sites if the site-specific EB method is applied. The following paragraphs describe the criteria for assigning crashes to the freeway in the subject travel direction and its individual sites.

All crashes that occur on the freeway are assigned to the subject or opposing travel direction. Crashes assigned to the subject travel direction that (a) occur in the freeway lanes or roadside associated with the subject travel direction (excluding those involving a vehicle from the opposing direction that has crossed over the median), or (b) occur in the median by a vehicle traveling in the subject travel direction prior to the occurrence of events leading to the crash, or (c) occur beyond the median and include a vehicle traveling in the subject travel direction prior to the occurrence of events leading to the crash. All crashes that are not assigned to the subject travel direction are assigned to the opposing travel direction.

All crashes that are assigned to the subject direction of travel are classified as either a speed-change-lane-related crash or a segment-related crash. Speed-change-related crashes include all crashes that are located between the gore point and the taper point of a speed-change lane and that (a) involve vehicles in the speed-change lane, (b) involve vehicles in the freeway lanes on the same side of the freeway as the speed-change lane, or (c) occur in the median by a vehicle traveling in a lane on the same side of the freeway as the speed-change lane and in the same basic direction as vehicles in the speed-change lane. All freeway crashes that are not classified as speed-change-related crashes are considered to be freeway segment crashes.

2.7 PREDICTIVE MODEL FOR FREEWAY SEGMENTS WITH HOV OR HOT LANES

The predictive models for freeways segments are described in this section. Each model typically consists of a safety performance function (SPF), one or more SPF adjustment factors (AFs), a calibration factor, a severity distribution, and crash type distribution. *All variables in this section that describe SPF or AF input values are defined in Section 2.5.2.*

The SPFs are used to estimate the predicted average crash frequency of a segment with base conditions. The SPFs, like all regression models, estimate the value of the dependent variable as a function of a set of independent variables. The independent variables for the freeway segment SPFs include the segment's AADT volume and length. The freeway segment SPFs are summarized in Table 4.

Table 4. SPFs for freeway segments.

Cross Section (x)	Crash Type (y)	SPF Equations
n GP through lanes (n)	Multiple vehicle (mv)	Equation 14
	All types (at)	Equation 14

Some transportation agencies may have performed statistically sound studies to develop their own jurisdiction-specific SPFs. These SPFs may be substituted for the SPFs presented in this section. Criteria for the development of SPFs for use in the predictive method are addressed in the appendix for Part C of the HSM (*4*).

Each SPF has an associated overdispersion parameter *k*. The overdispersion parameter provides an indication of the statistical reliability of the SPF. The closer the overdispersion parameter is to zero, the more statistically reliable the SPF. This parameter is used in the EB Method that is discussed in the appendix for Part C of the HSM (*4*).

The AFs applicable to the SPFs presented in Table 4 are summarized in Table 5.

Table 5. SPF adjustment factors for freeway segments.

AF Variable	AF Description	AF Equations
$AF_{1,fs,ac,y,as}$	Lateral separation and access type	Equation 16
$AF_{2,fs,ac,y,as}$	Inside shoulder width	Equation 17
$AF_{3,fs,ac,y,as}$	Outside shoulder width	Equation 18
$AF_{4,fs,ac,y,as}$	Median width	Equation 19
$AF_{5,fs,ac,y,as}$	Median barrier	Equation 20
$AF_{6,fs,ac,at,as}$	Outside barrier	Equation 22
$AF_{7,fs,ac,y,as}$	Type C weaving section	Equation 24
$AF_{8,fs,ac,y,as}$	Average speed differential	Equation 25
$AF_{9,fs,ac,y,as}$	High-volume hours	Equation 26

Note: Subscripts to the AF variables use the following notation:

- Site type w ($w = fs$: freeway segment, en: ramp entrance speed-change lane, ex: ramp exit speed-change lane)
- Cross section x ($x = n$: freeway with n GP through lanes, ac: any cross section)
- Crash type y ($y = mv$: multiple vehicle, at: all types)
- Severity z ($z = as$: all severities)

Many of the AFs in Table 5 are developed for specific site types and crash types. This approach was undertaken to make the predictive model sensitive to the geometric design and traffic control features of specific sites, in terms of their influence on specific crash types. The subscripts for each AF variable indicate the sites and crash types to which each AF is applicable. The subscript definitions are provided in the table footnote. In some cases, an AF is applicable to several crash types. In these cases, the subscript retains the generic letter y. The discussion of these AFs in Section 2.7.2 identifies the specific crash types to which they apply.

2.7.1 Safety Performance Functions for Freeway Segments with HOV or HOT Lanes

The SPFs for freeway segments are presented in this section. Specifically, SPFs are provided for one-directional freeway segments with two to seven GP through lanes. The range of AADT volume for which these SPFs are applicable is shown in Table 6. Application of the SPFs to sites with AADT volumes substantially outside these ranges may not provide reliable results.

Table 6. Applicable AADT volume ranges for freeway segment SPFs.

Cross Section (x)	Applicable AADT Volume Range (veh/day)
2 GP through lanes	0 to 121,000
3 or more GP through lanes	0 to 162,500

The base conditions for the SPFs for freeway segments are presented in the following list of variables (these variables are defined in Section 2.5.2):

- Lateral separation — Lane line
- HO lane access type — Continuous
- Inside shoulder width (paved) — 2 ft
- Outside shoulder width (paved) — 10 ft
- Median width — 22 ft
- Length of inside (median) barrier — 0.0 mi (not present)
- Length of outside (roadside) barrier — 0.0 mi (not present)
- One-sided Type C weaving section — Not present
- Average speed difference between HO lane and leftmost GP lane — 0.0 mi/h
- Proportion of hours where volume exceeds 1,000 veh/h/ln — 0.0

The SPFs for freeway segments are represented using the following equation:

$$N_{spf,fs,n,y,as} = L_{s,fs} \times \exp\left(a + b \times \ln[AADT_{fs}]\right) \quad (14)$$

where

$N_{spf,fs,n,y,as}$ = predicted average crash frequency of a freeway segment with base conditions, n lanes, crash type y ($y = mv$: multiple vehicle, at: all types), and all severities as (crashes/yr);

$L_{s,fs}$ = length of freeway segment (mi);

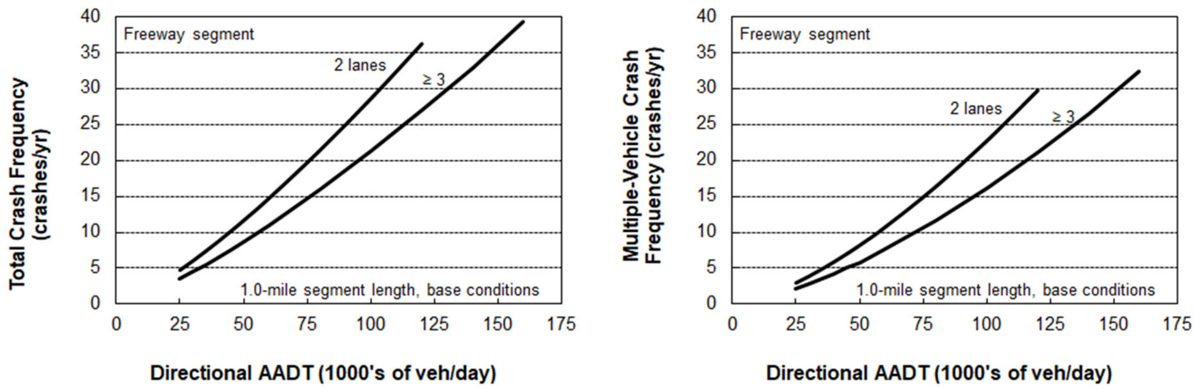
a, b = regression coefficients; and

$AADT_{fs}$ = one-directional AADT volume of freeway segment (including vehicles in the HO lane) (veh/day).

The SPF coefficients and the overdispersion parameter coefficients are provided in Table 7. The SPFs are illustrated in Figure 12.

Table 7. SPF coefficients for freeway segments.

Number of GP Through Lanes (*n*)	Crash Type (*y*)	SPF Coefficient *a*	SPF Coefficient *b*	Overdispersion Parameter Coefficient *c*	Overdispersion Parameter Coefficient *d*
2	All crash types (*at*)	–11.590	1.298	–2.631	–0.706
	Multiple vehicle (*mv*)	–13.846	1.474	–2.429	–0.667
3 or more	All crash types (*at*)	–11.884	1.298	–2.631	–0.706
	Multiple vehicle (*mv*)	–14.186	1.474	–2.429	–0.667



a. Total crash frequency (all crash types) **b. Multiple-vehicle crash frequency**

Figure 12. Graphical form of the SPFs for freeway segments.

The value of the overdispersion parameter associated with the SPFs for freeway segments is determined as a function of the segment length. This value is computed using Equation 15.

$$k_{fs,n,y,as} = \exp(c) \times (L_{s,fs})^d \quad (15)$$

where

$k_{fs,n,y,as}$ = overdispersion parameter for freeway segments with *n* lanes, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*.

2.7.2 SPF Adjustment Factors for Freeway Segments with HOV or HOT Lanes

The AFs for geometric design and traffic control features of freeway segments are presented in this section. Several AFs described in this section include a variable defining the proportion of the segment's length along which a particular feature (e.g., median barrier) is present. Guidance is offered herein for computing each proportion. The concept underlying this guidance is that the computed proportion should equal the total length of the feature divided by the length of the segment.

***$AF_{1,fs,ac,y,as}$*—Lateral Separation and Access Type**

Two AFs are used to describe the relationship between HO lane lateral separation, HO lane access type, and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs, ac, mv, as*).

The base condition is lane line separation and continuous access. The AFs for lateral separation and access type are described using the following equation:

$$AF_{1,fs,ac,y,as} = \exp\left(a + b \times W_{\text{buffer}} + c \times \frac{X_{DA}}{n_{GPL}}\right) \quad (16)$$

where

$AF_{1,fs,ac,y,as}$ = adjustment factor for lateral separation and access type in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*;

W_{buffer} = width of the buffer between the HO lane and inside GP through lane (ft);

X_{DA} = distance between the last HO lane egress point and the gore point of the next exit ramp (mi); and

n_{GPL} = number of GP through lanes in the subject travel direction (lanes).

The coefficients for Equation 16 are provided in Table 8. As indicated by this table, buffer width has an effect on the AF value only if the lateral separation is "flush buffer." Hence, this width is needed only if flush buffer separation is present and, when it is needed, it is limited to a value in the range of 1.0 to 12.0 feet.

Also as indicated by Table 8, the distance X_{DA} has an effect on AF value only if HO lane access is provided via at-grade entrance and exit zones. Moreover, this term of the AF is only applicable if the subject site begins and ends within the distance X_{DA} [i.e., an X_{DA} value of 0.0 is used if (a) the HO lane has continuous access, (b) the site ends before or at the egress point, or (c) the site starts at or after the gore point]. The AF is applicable to "X_{DA}/n_{GPL}" ratios that range from 0.0 to 0.25 miles per lane. If the computed ratio exceeds 0.25, it should be set to 0.25 when used to compute the AF value.

Details regarding the measurement of the variables associated with this AF are provided in Section 2.5.2.

Table 8. Coefficients for lateral separation and access type AF—freeway segments.

Lateral Separation	Access Type	Crash Type (y)	AF Coefficients a	b	c
Lane line	Continuous	All crash types (at)	0.0	0.0	0.0
		Multiple vehicle (mv)	0.0	0.0	0.0
	At-grade entrance and exit zones	All crash types (at)	0.0	0.0	−0.326
		Multiple vehicle (mv)	0.0	0.0	−0.409
Flush buffer	At-grade entrance and exit zones	All crash types (at)	0.215	−0.0622	−0.326
		Multiple vehicle (mv)	0.164	−0.0588	−0.409
Pylon buffer	At-grade entrance and exit zones	All crash types (at)	−0.234	0.0	−0.326
		Multiple vehicle (mv)	−0.229	0.0	−0.409
Barrier	At-grade entrance and exit zones	All crash types (at)	−0.234	0.0	−0.326
		Multiple vehicle (mv)	−0.229	0.0	−0.409

$AF_{2,fs,ac,y,as}$—Inside Shoulder Width

Two AFs are used to describe the relationship between average inside shoulder width and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is a 2-ft inside shoulder width. The AFs are described using the following equation:

$$AF_{2,fs,ac,y,as} = \exp(a \times [W_{is} - 2]) \qquad (17)$$

where

$AF_{2,fs,ac,y,as}$ = adjustment factor for inside shoulder width in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*; and

W_{is} = paved inside shoulder width (ft).

The coefficient for Equation 17 is provided in Table 9. The AF is applicable to inside shoulder widths in the range of 1 to 14 ft.

Table 9. Coefficients for inside shoulder width AF—freeway segments.

Cross Section (x)	Crash Type (y)	AF Variable	AF Coefficient (a)
Any cross section (ac)	All crash types (at)	$AF_{2,fs,ac,at,as}$	–0.0191
	Multiple vehicle (mv)	$AF_{2,fs,ac,mv,as}$	–0.0210

$AF_{3,fs,ac,y,as}$—Outside Shoulder Width

Two AFs are used to describe the relationship between average outside shoulder width and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and

- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is a 10-ft outside shoulder width. The AFs are described using the following equation:

$$AF_{3,fs,ac,y,as} = \exp(a \times [W_s - 10]) \quad (18)$$

where

$AF_{3,fs,ac,y,as}$ = adjustment factor for outside shoulder width in a freeway segment with any cross section *ac*; for crash type *y*, and all severities *as*; and

W_s = paved outside shoulder width (ft).

The coefficient for Equation 18 is provided in Table 10. The AF is applicable to outside shoulder widths in the range of 1 to 14 ft.

Table 10. Coefficients for outside shoulder width AF—freeway segments.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{3,fs,ac,at,as}$	–0.00686
	Multiple vehicle (*mv*)	$AF_{3,fs,ac,mv,as}$	–0.00699

$AF_{4,fs,ac,y,as}$—Median Width

Two AFs are used to describe the relationship between median width and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is a 22-ft median width. The AFs are described using the following equation:

$$AF_{4,fs,ac,y,as} = \exp(a \times [W_m - 22]) \quad (19)$$

where

$AF_{4,fs,ac,y,as}$ = adjustment factor for median width in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*; and

W_m = median width (ft).

The coefficient for Equation 19 is provided in Table 11. The AF is applicable to median widths in the range of 4 to 120 ft. Details regarding the measurement of median width are provided in Section 2.5.2.

Table 11. Coefficients for Median Width AF—Freeway Segments

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{4,fs,ac,at,as}$	–0.00162
	Multiple vehicle (*mv*)	$AF_{4,fs,ac,mv,as}$	–0.00173

$AF_{5,fs,ac,y,as}$—Median Barrier

Two AFs are used to describe the relationship between median barrier presence and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is "no barrier present in the median." The AFs are described using the following equation:

$$AF_{5,fs,ac,y,as} = (1.0 - P_{ib}) \times 1.0 + P_{ib} \times \exp(a) \tag{20}$$

with

$$P_{ib} = \frac{L_{ib}}{L_{s,fs}} \tag{21}$$

where

$AF_{5,fs,ac,y,as}$ = adjustment factor for median barrier in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*;

P_{ib} = proportion of site length with a barrier present in the median (i.e., inside);

L_{ib} = length of lane paralleled by inside (median) barrier (mi); and

$L_{s,fs}$ = length of freeway segment (mi).

The coefficient for Equation 20 is provided in Table 12. This AF is applicable to cable barrier, concrete barrier, guardrail, and bridge rail.

Table 12. Coefficients for median barrier AF—freeway segments.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{5,fs,ac,at,as}$	0.231
	Multiple vehicle (*mv*)	$AF_{5,fs,ac,mv,as}$	0.290

$AF_{6,fs,ac,at,as}$—Outside Barrier

One AF is used to describe the relationship between outside barrier presence and predicted crash frequency. The SPF to which it applies is identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*.

The base condition is "no barrier present in the clear zone." The AFs are described using the following equation:

$$AF_{6,fs,ac,at,as} = (1.0 - P_{ob}) \times 1.0 + P_{ob} \times \exp(-0.0481) \tag{22}$$

with

$$P_{ob} = \frac{L_{ob}}{L_{s,fs}} \tag{23}$$

where

$AF_{6,fs,ac,at,as}$ = adjustment factor for outside (roadside) barrier in a freeway segment; for any cross section *ac*, all crash types *at*, and severities *as*;

P_{ob} = proportion of site length with a barrier present on the outside (roadside);

L_{ob} = length of lane paralleled by outside (roadside) barrier (mi); and

$L_{s,fs}$ = length of freeway segment (mi).

This AF is applicable to cable barrier, concrete barrier, guardrail, and bridge rail.

$AF_{7,fs,ac,y,as}$—Type C Weaving Section

Two AFs are used to describe the relationship between one-sided Type C weaving section presence and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is "one-sided Type C weaving section not present." The AFs are described using the following equation:

$$AF_{7,fs,ac,y,as} = \exp(a \times I_C) \quad (24)$$

where

$AF_{7,fs,ac,y,as}$ = adjustment factor for one-sided Type C weaving section presence in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*; and

I_C = indicator variable for weaving section presence (= 1.0 if one-sided Type C weaving section present; 0.0 otherwise).

The coefficient for Equation 24 is provided in Table 13. The AF is applicable to segments that start and end within the one-sided Type C weaving section.

Table 13. Coefficients for Type C weaving section AF—freeway segments.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{7,fs,ac,at,as}$	0.224
	Multiple vehicle (*mv*)	$AF_{7,fs,ac,mv,as}$	0.254

$AF_{8,fs,ac,y,as}$—Average Speed Differential

Two AFs are used to describe the relationship between the "average speed differential" and predicted crash frequency. This differential represents the difference between the average speed of the inside GP lane and the average speed of the HO lane(s). The SPFs to which the AFs apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is an average speed differential of 0.0 mi/h. The AFs are described using the following equation:

$$AF_{8,fs,ac,y,as} = \exp(a \times \Delta_v) \quad (25)$$

where

$AF_{8,fs,ac,y,as}$ = adjustment factor for average speed differential in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *as*; and

Δ_v = average speed differential between the inside GP lane and the HO lane(s) (= speed in HO lane minus speed in GP lane) (mi/h).

The coefficient for Equation 24 is provided in Table 14. As indicated by this table, the average speed differential has an effect on the AF value only if the lateral separation is "continuous" or "flush buffer." Hence, the speed differential variable Δ_v is needed only if continuous or flush buffer separation is present and, when it is needed, it is limited to a value in the range of 0.0 to 15 mi/h.

Details regarding the measurement of speed differential are provided in Section 2.5.2. An equation is provided in that section for estimating a default speed differential value when conditions do not permit its measurement for the subject segment.

Table 14. Coefficients for average speed differential AF—freeway segments.

Lateral Separation	Access Type	Crash Type (*y*)	AF Coefficient (*a*)
Lane line	Continuous	All crash types (*at*)	0.0178
		Multiple vehicle (*mv*)	0.0230
	At-grade entrance and exit zones	All crash types (*at*)	0.0178
		Multiple vehicle (*mv*)	0.0230
Flush buffer	At-grade entrance and exit zones	All crash types (*at*)	0.0178
		Multiple vehicle (*mv*)	0.0230
Pylon buffer	At-grade entrance and exit zones	All crash types (*at*)	0.0
		Multiple vehicle (*mv*)	0.0
Barrier	At-grade entrance and exit zones	All crash types (*at*)	0.0
		Multiple vehicle (*mv*)	0.0

$AF_{9,fs,ac,y,as}$—High-Volume Hours

As volume nears capacity, average freeway speed tends to decrease, and headway is reduced. Logically, these changes have some influence on crash characteristics, including crash frequency, crash type, and crash severity. This AF was developed to provide some sensitivity to volume variation during the average day and specifically to those peak hours where traffic volume is likely to be near (or in excess of) capacity.

A statistic was developed to describe the degree of volume concentration during peak hours of the average day. It represents the proportion of hours in the average day where the volume exceeds 1,000 vehicles per hour per lane (veh/h/ln). It has a value of zero if the volume on the associated segment does not exceed the threshold value for any hour of the day. It has a value of one if the volume during each hour of the average day exceeds the threshold value. In general, its value is large when hourly volumes are continuously high.

Typical freeway speed–volume relationships show that the average speed tends to drop as flow rates increase beyond 1,000 veh/h/ln. This trend suggests that drivers reduce their speed to improve their comfort and safety as their headway gets shorter than 3.6 s/veh (=3,600/1,000).

This AF is similar to the High Volume AF described in Chapter 18 of the HSM Supplement (*2*). However, the AF in Chapter 18 is based on the *proportion of the AADT* (that occurs during hours where the volume exceeds 1,000 veh/h/ln) as opposed to the proportion of hours in the average day.

Two AFs are used to describe the relationship between volume concentration and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, and any number of lanes (*fs*, *ac*, *at*, *as)*; and
- SPF for all severities, multiple-vehicle crashes, and any number of lanes (*fs*, *ac*, *mv*, *as*).

The base condition is "no hours having a volume that exceeds 1,000 veh/h/ln." The AFs are described using the following equation:

$$AF_{9,fs,ac,y,as} = \exp(a \times P_{hvh}) \quad (26)$$

where

$AF_{9,fs,ac,y,as}$ = adjustment factor for high-volume hours in a freeway segment; for any cross section *ac*, crash type *y*, and all severities *ac*; and

P_{hvh} = proportion of hours where volume exceeds 1,000 veh/h/ln.

The coefficient for Equation 26 is provided in Table 15. The AF is applicable to P_{hvh} values in the range of 0.0 to 0.766.

Table 15. Coefficients for high-volume hours AF—freeway segments.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{9,fs,ac,at,as}$	0.290
	Multiple vehicle (*mv*)	$AF_{9,fs,ac,mv,as}$	0.412

2.7.3 Severity Distribution for Freeway Segments with HOV or HOT Lanes

The severity distribution for freeway segments is presented in this section. The severity distribution is used in the predictive model to estimate the average crash frequency for the following severity levels: fatal *K*, incapacitating injury *A*, non-incapacitating injury *B*, possible injury *C*, and property-damage-only *PDO*.

The severity distribution proportions are computed using a severity distribution function (SDF). The SDF was developed as a logistic regression model using observed crash data. The SDF, like all regression models, estimates the distribution value as a function of a set of independent variables. The independent variables include various geometric design and traffic control features.

There is one SDF associated with each severity level *j* in the predictive model. The SDF for level *j* predicts the proportion of crashes with severity level *j*, based on various geometric design and traffic control features at the subject site. The SDF also contains a calibration factor that is used to calibrate the SDF to local conditions.

The distribution value for severity level *j* is multiplied by the total crash frequency (all severities) to obtain the total crash frequency for the specified severity level. Similarly, the distribution value can be multiplied by the multiple-vehicle crash frequency or the single-vehicle crash frequency to obtain the predicted crash frequency for a specific crash type and severity level. The predicted average crash frequency is obtained from Equation 2, Equation 3, or Equation 5 as a predicted value. The expected value equivalent should be used if the EB Method is applied.

The general model form for the severity distribution prediction equation for freeway segments is shown in the following equation.

$$N_{p,fs,n,y,j} = N_{p,fs,n,y,as} \times P_{fs,ac,at,j} \tag{27}$$

where

$N_{p,fs,n,y,j}$ = predicted average crash frequency of a freeway segment with *n* lanes, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and severity level *j* (*j* = *K*: fatal, *A*: incapacitating injury, *B*: non-incapacitating injury, *C*: possible injury, *PDO*: property-damage-only) (crashes/yr);

$N_{p,fs,n,y,as}$ = predicted average crash frequency of a freeway segment with *n* lanes, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr); and

$P_{fs,ac,at,j}$ = proportion of crashes with severity level *j* (*j* = *K*: fatal, *A*: incapacitating injury, *B*: non-incapacitating injury, *C*: possible injury, *PDO*: property-damage-only) for all crash types *at* on a freeway segment with any cross section *ac*.

The SDFs for freeway segments are described by the following equations.

$$P_{fs,ac,at,K} = \frac{\exp(V_{fs,K+A})}{\frac{1.0}{C_{sdf,fs}} + \exp(V_{fs,K+A}) + \exp(V_{fs,B}) + \exp(V_{fs,C})} \times P_{K|K+A,fs,ac,at} \tag{28}$$

$$P_{fs,ac,at,A} = \frac{\exp(V_{fs,K+A})}{\frac{1.0}{C_{sdf,fs}} + \exp(V_{fs,K+A}) + \exp(V_{fs,B}) + \exp(V_{fs,C})} \times (1.0 - P_{K|K+A,fs,ac,at}) \tag{29}$$

$$P_{fs,ac,at,B} = \frac{\exp(V_{fs,B})}{\frac{1.0}{C_{sdf,fs}} + \exp(V_{fs,K+A}) + \exp(V_{fs,B}) + \exp(V_{fs,C})} \tag{30}$$

$$P_{fs,ac,at,C} = \frac{\exp(V_{fs,C})}{\frac{1.0}{C_{sdf,fs}} + \exp(V_{fs,K+A}) + \exp(V_{fs,B}) + \exp(V_{fs,C})} \tag{31}$$

$$P_{fs,ac,at,PDO} = 1.0 - (P_{fs,ac,at,K} + P_{fs,ac,at,A} + P_{fs,ac,at,B} + P_{fs,ac,at,C}) \tag{32}$$

where

$V_{fs,j}$ = systematic component of crash severity likelihood for severity level *j* for a freeway segment;

$P_{K|K+A,fs,ac,at}$ = probability of a fatal *K* crash given that the crash has a severity of either fatal or incapacitating injury *A* for all crash types *at* on a freeway segment with any cross section *ac*; and

$C_{sdf,fs}$ = calibration factor to adjust SDF for local conditions for freeway segments.

The first term of Equation 28 and Equation 29 estimates the probability of a fatal or incapacitating injury crash. The second term of Equation 28 (i.e., $P_{K|K+A,fs,ac,at}$) is used to convert the estimate into the probability of a fatal crash. A value of 0.209 is used for $P_{K|K+A,fs,ac,at}$ based on an analysis of fatal and incapacitating injury crashes on freeway segments with HO lanes.

A model for estimating the systematic component of crash severity for freeway segments is described by the following equation.

$$V_{fs,j} = a + \left(b \times \ln\left[AADT_{fs}\right]\right) + (c \times I_{65}) + (d \times I_{70}) + (e \times I_{\geq 3GPL}) + \left(f \times I_{\text{at-grade}}\right) + (g \times P_{ob}) + (h \times P_{ib}) + (i \times I_{R24}) + (j \times I_{\text{flush}}) + (k \times I_{\text{flush}} \times W_{\text{buffer}}) + (l \times P_c) + (m \times P_{hvh}) + \left(n \times X_{b,ent}\right) + \left(p \times X_{e,ext}\right) + \left(q \times \ln\left[AADT_{b,ent}\right]\right) + \left(r \times \ln\left[AADT_{e,ext}\right]\right) \quad (33)$$

where

$AADT_{fs}$ = one-directional AADT volume of freeway segment (including vehicles in the HO lane) (veh/day);

I_{65} = 65mi/h speed limit indicator variable (= 1.0 if speed limit is 65 mi/h, 0.0 otherwise);

I_{70} = 70mi/h speed limit indicator variable (= 1.0 if speed limit is 70 mi/h, 0.0 otherwise);

$I_{\geq 3GPL}$ = 3 to 7 GP lanes indicator variable (= 1.0 if 3 or more GP lanes, 0.0 otherwise);

$I_{\text{at-grade}}$ = HO lane access type indicator variable (= 1.0 if HO lane access in vicinity of subject site has at-grade entrance and exit zones, 0.0 otherwise);

P_{ob} = proportion of segment length with a barrier present on the outside (roadside);

P_{ib} = proportion of segment length with a barrier present in the median (i.e., inside);

I_{R24} = HO lane access restriction indicator variable (= 1.0 if full-time HO lane, 0.0 otherwise);

I_{flush} = lateral separation indicator variable (= 1.0 if HO lane is separated from the GP lane by a flush buffer, 0.0 otherwise);

W_{buffer} = width of the buffer between the HO lane and inside GP through lane (ft);

P_c = proportion of segment length with a horizontal curve;

P_{hvh} = proportion of hours where volume exceeds 1,000 veh/h/ln;

$X_{b,ent}$ = distance from segment begin milepost to nearest upstream entrance ramp gore point (mi);

$X_{e,ext}$ = distance from segment end milepost to nearest downstream exit ramp gore point (mi);

$AADT_{b,ent}$ = AADT volume of entrance ramp located at distance $X_{b,ent}$ upstream of the subject segment (veh/day);

$AADT_{e,ext}$ = AADT volume of exit ramp located at distance $X_{e,ext}$ downstream of the subject segment (veh/day); and

$a, b, \ldots, q, r$ = regression coefficients.

The SDF coefficients in Equation 33 are provided in

Table 16.

Table 16. SDF coefficients for freeway segments.

SDF Coefficient	Coefficient Value by Severity Level *j*		
	Fatal or Incapacitating Injury (*K*+*A*)	Non-Incapacitating Injury (*B*)	Possible Injury (*C*)
a	5.207	3.946	2.238
b	–0.703	–0.513	–0.281
c	0.748	0.411	0.0
d	0.803	0.474	0.0
e	0.264	0.0887	0.0
f	–0.308	–0.308	–0.154
g	–0.104	0.0	0.0
h	–0.0989	0.0	0.0
i	0.185	0.102	0.0
j	–0.447	–0.281	–0.123
k	0.0374	0.0285	0.0
l	0.0306	0.0306	0.0
m	–0.199	–0.199	0.104
n	–0.0372	–0.0372	0.0
p	–0.0598	–0.0598	–0.0538
q	–0.0762	–0.0524	0.0
r	–0.0789	0.0	0.0

The posted speed limit is limited to 60, 65, and 70 mi/h. The number of GP lanes is limited to a range of 2 to 7.

The variable P_{ob} is computed as the ratio of the length of lane paralleled by outside (roadside) barrier divided by the length of the segment (as shown in Equation 23). Similarly, the variable P_{ib} is computed as the ratio of the length of lane paralleled by inside (median) barrier divided by the length of the segment (as shown in Equation 21).

Buffer width is needed only if flush buffer separation is present and, when it is needed, it is limited to a value in the range of 1.0 to 12.0 feet.

The variable P_c is computed as the ratio of the length of horizontal curve in the segment divided by the length of the segment.

The proportion of hours in the average day where the volume exceeds 1,000 veh/h/ln P_{hvh} is computed using the average hourly volume distribution associated with the subject segment. This distribution will typically be computed using the data obtained from the continuous traffic counting station that (a) is nearest to the subject freeway and (b) has similar traffic demand and peaking characteristics. The SDF is applicable to P_{hvh} values in the range of 0.0 to 0.766.

Additional discussion of this variable is provided in Section 2.7.2 for the High-Volume Hours AF.

The $X_{b,ent}$ and $AADT_{b,ent}$ variables describe the distance to (and volume of) the nearest upstream entrance ramp. Similarly, the $X_{e,ext}$ and $AADT_{e,ext}$ variables describe the distance to (and volume of) the nearest downstream exit ramp. Only those ramps that contribute volume to the subject segment are of interest. Hence, a downstream entrance ramp is not of interest. For similar reasons, an upstream exit ramp is not of interest. If the ramp does not exist or it is located more than 2.0 mi from the segment, then the distance $X_{i,j}$ can be set to 2.0 mi in the model to obtain the correct results.

The sign of a coefficient in

Table 16 indicates the direction of the change in the proportion of crashes associated with a change in the corresponding variable. For example, the negative coefficient associated with coefficient *b* indicates that the proportion of fatal *K* crashes decreases with an increase in volume. A similar trend is indicated for barrier presence on incapacitating injury *A*, non-incapacitating injury *B*, and possible injury *C* crashes. By inference, the proportion of property-damage-only *PDO* crashes *increases* with an increase in volume.

2.7.4 Crash Type Distribution for Freeway Segments with HOV or HOT Lanes

The crash type distributions for freeway segments are presented in this section. They are used in the predictive model to estimate the average crash frequency for typical crash types.

The four crash frequency estimates that are used to compute the crash type distribution are:

- Multiple-vehicle crashes $N_{p,fs,n,mv,as}$ (from Equation 3);
- Single-vehicle crashes $N_{p,fs,n,sv,as}$ (from Equation 5);

The estimates needed to compute the crash type distribution are obtained from the aforementioned equations as predicted values; however, their expected value equivalents should be used if the EB Method is applied.

The general model form of the crash type distribution prediction equation is shown in the following equation.

$$N_{p,fs,n,y(j),as} = N_{p,fs,n,y,as} \times P_{fs,ac,y(j),as} \quad (34)$$

where

$N_{p,fs,n,y(j),as}$ = predicted average crash frequency of a freeway segment with *n* lanes, subtype *j* of crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle), and all severities *as* (crashes/yr);

$N_{p,fs,n,y,as}$ = predicted average crash frequency of a freeway segment with *n* lanes, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle), and all severities *as* (crashes/yr); and

$P_{fs,ac,y(j),as}$ = proportion of crash-type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle) that are subtype *j* (*j* = rear end, head on, etc.) and all severities *as* on a freeway segment with any cross section *ac*.

Each application of Equation 34 requires one crash type distribution value (i.e., proportion) for each crash subtype *j* of crash type *y*. These values are shown in Table 17.

Table 17. Default distribution of crash type for freeway segments.

Crash Type Category	Crash Type (*j*)		Proportion of Crashes
Multiple-vehicle	Head-on		0.005
	Right-angle		0.039
	Rear-end		0.686
	Sideswipe		0.218
	Other multiple-vehicle crashes		0.052
		Total:	1.000
Single-vehicle	Crash with animal		0.006
	Crash with fixed object		0.780
	Crash with other object		0.118
	Crash with parked vehicle		0.000
	Other single-vehicle crashes		0.096
		Total:	1.000

2.8 PREDICTIVE MODEL FOR FREEWAY SPEED-CHANGE LANES WITH HOV OR HOT LANES

The predictive models for speed-change lane sites are described in this section. Each model typically consists of a safety performance function (SPF), one or more SPF adjustment factors (AFs), a calibration factor, a severity distribution, and a crash type distribution. *All variables in this section that describe SPF or AF input values are defined in Section 2.5.2.*

The SPFs are used to estimate the predicted average crash frequency of a site with base conditions. The SPFs, like all regression models, estimate the value of the dependent variable as a function of a set of independent variables. The independent variables for the speed-change lane SPFs include the AADT volume of the freeway, AADT volume of the ramp, and speed-change lane length. The speed-change lane SPFs are summarized in Table 18.

Table 18. Safety performance functions for speed-change lanes.

Site Type (*w*)	Cross Section (*x*)	Crash Type (*y*)	SPF Equations
Ramp entrance speed-change lane (*en*)	All cross sections (*ac*)	Multiple vehicle (*mv*)	Equation 35
		All types (*at*)	Equation 35
Ramp exit speed-change lane (*ex*)	All cross sections (*ac*)	Multiple vehicle (*mv*)	Equation 37
		All types (*at*)	Equation 37

Some transportation agencies may have performed statistically sound studies to develop their own jurisdiction-specific SPFs. These SPFs may be substituted for the SPFs presented in this section. Criteria for the development of SPFs for use in the predictive method are addressed in the calibration procedure presented in the appendix for Part C of the HSM (*4*).

Each SPF has an associated overdispersion parameter *k*. The overdispersion parameter provides an indication of the statistical reliability of the SPF. The closer the overdispersion parameter is to zero, the more statistically reliable the SPF. This parameter is used in the EB Method that is discussed in the appendix for Part C of the HSM (*4*).

The AFs applicable to the SPFs presented in Table 18 are summarized in Table 19.

Table 19. SPF adjustment factors for speed-change lanes.

AF Variable	AF Description	AF Equations
$AF_{1,w,ac,y,as}$	Lateral separation and access type	Equation 39
$AF_{2,w,ac,y,as}$	Inside shoulder width	Equation 40
$AF_{3,w,ac,y,as}$	Outside shoulder width	Equation 41
$AF_{4,w,ac,y,as}$	Median width	Equation 42
$AF_{5,w,ac,y,as}$	Median barrier	Equation 43
$AF_{6,w,ac,at,as}$	Outside barrier	Equation 45
$AF_{8,w,ac,y,as}$	Average speed differential	Equation 47
$AF_{10,w,ac,y,as}$	Number of HO lanes	Equation 48

Note: Subscripts to the AF variables use the following notation:

- Site type *w* (*w* = *fs*: freeway segment, *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane)
- Cross section *x* (*x* = *n*: freeway with *n* GP through lanes, *ac*: any cross section)
- Crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types)
- Severity *z* (*z* = *as*: all severities)

Many of the AFs in Table 19 are developed for specific site types and crash types. This approach was undertaken to make the predictive model sensitive to the geometric design and traffic control features of specific sites, in terms of their influence on specific crash types. The subscripts for each AF variable indicate the sites and crash types to which each AF is applicable. The subscript definitions are provided in the table footnote. In some cases, an AF is applicable to several crash types. In these cases, the subscript retains the generic letter *y*. The discussion of these AFs in Section 2.8.2 identifies the specific crash types to which they apply.

2.8.1 Safety Performance Functions for Speed-Change Lanes with HOV or HOT Lanes

The SPFs for speed-change lane sites are presented in this section. Specifically, SPFs are provided for ramp entrance and ramp exit sites adjacent to freeways with two to seven GP through lanes. A speed-change lane can be represented as one site or it can be subdivided into two or more sites if needed to comply with the guidelines provided in Section 2.6.2. The range of AADT volume for which these SPFs are applicable is shown in Table 20. Application of the SPFs to sites with AADT volumes substantially outside these ranges may not provide reliable results.

Table 20. Applicable AADT volume ranges for speed-change lane SPFs.

Site Type (*w*)	Applicable AADT Volume Range (veh/day)	
	Freeway	Ramp
Ramp entrance speed-change lane (*en*)	0 to 162,500	0 to 79,000
Ramp exit speed-change lane (*ex*)	0 to 162,500	0 to 91,000

Ramp Entrance Speed-Change Lanes

The base conditions for the SPFs for ramp-entrance speed-change lanes are presented in the following list of variables (these variables are defined in Section 2.5.2):

- Lateral separation — Lane line
- HO lane access type — Continuous
- Inside shoulder width (paved) — 2 ft
- Outside shoulder width (paved) — 10 ft
- Median width — 22 ft
- Length of inside (median) barrier — 0.0 mi (not present)
- Length of outside (roadside) barrier — 0.0 mi (not present)
- Average speed difference between HO lane and leftmost GP lane — 0.0 mi/h
- Number of HO lanes — 1 lane

The SPFs for ramp entrance speed-change lanes are represented using the following equation:

$$N_{spf,en,ac,y,as} = L_{s,en} \times \exp\left(a + b \times \ln[\,AADT_f] + e \times \ln[\,AADT_{en}]\right) \quad (35)$$

where

$N_{spf,en,ac,y,as}$ = predicted average crash frequency of a ramp entrance speed-change lane site with base conditions, all cross sections *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$AADT_{en}$ = AADT volume of entrance ramp (veh/day);

$AADT_f$ = one-directional AADT volume of freeway in speed-change lane site (including vehicles in the HO lane) (veh/day); and

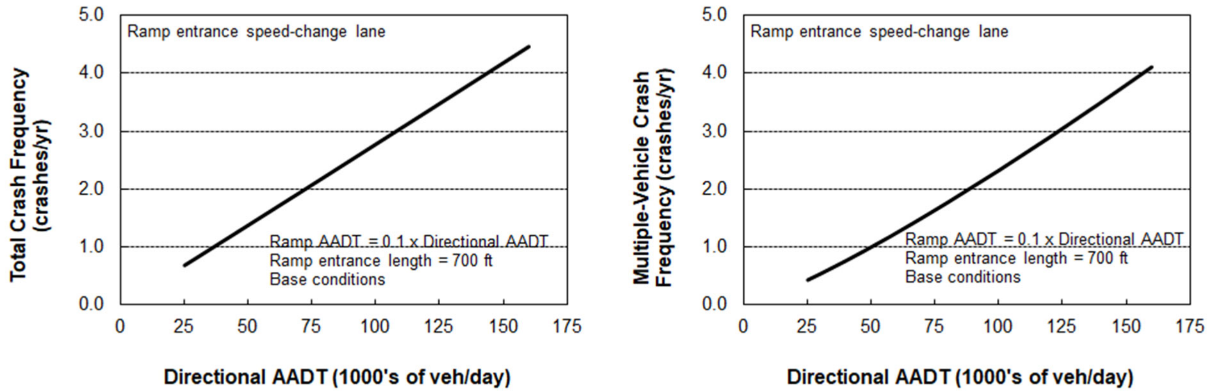
$L_{s,en}$ = length of ramp entrance speed-change lane site (≤ length of ramp entrance speed-change lane, as measured from gore point to taper point) (mi).

The length of the ramp entrance speed-change lane L_{en} is shown in Figure 3. The length of the subject speed-change lane site being evaluated $L_{s,en}$ can equal length L_{en}. However, $L_{s,en}$ may be less than length L_{en} if needed to comply with the segmentation guidelines described in Section 2.6.2.

The SPF coefficients and the overdispersion parameter coefficients are provided in Table 21. The SPFs are illustrated in Figure 13.

Table 21. SPF coefficients for ramp entrance speed-change lanes.

	SPF Coefficient			Overdispersion Parameter Coefficient	
Crash Type (*y*)	*a*	*b*	*e*	*c*	*d*
All crash types (*at*)	–8.417	0.939	0.0703	–2.631	–0.706
Multiple vehicle (*mv*)	–10.890	1.123	0.0895	–2.429	–0.667



a. Total Crash Frequency (all crash types) **b. Multiple-Vehicle Crash Frequency**

Figure 13. Graphical form of the SPFs for ramp entrance speed-change lanes.

The value of the overdispersion parameter associated with the SPFs for ramp entrance speed-change lane sites is determined as a function of site length. This value is computed using Equation 36.

$$k_{en,ac,y,as} = \exp{(c)} \times \left(L_{s,en}\right)^d \tag{36}$$

where

$k_{en,ac,y,as}$ = overdispersion parameter for ramp entrance speed-change lane sites with any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*.

Ramp Exit Speed-Change Lanes

The base conditions for the SPFs for ramp-exit speed-change lanes are presented in the following list of variables (these variables are defined in Section 2.5.2):

- Lateral separation — Lane line
- HO lane access type — Continuous
- Inside shoulder width (paved) — 2 ft
- Outside shoulder width (paved) — 10 ft
- Median width — 22 ft
- Length of inside (median) barrier — 0.0 mi (not present)
- Length of outside (roadside) barrier — 0.0 mi (not present)
- Average speed difference between HO lane and leftmost GP lane — 0.0 mi/h
- Number of HO lanes — 1 lane

The SPFs for ramp exit speed-change lanes are represented using the following equation:

$$N_{spf,ex,ac,y,as} = L_{s,ex} \times \exp\left(a + b \times \ln[AADT_f] + e \times \ln[AADT_{ex}]\right) \tag{37}$$

where

$N_{spf,ex,ac,y,as}$ = predicted average crash frequency of a ramp exit speed-change lane site with base conditions, all cross sections *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr);

$AADT_{ex}$ = AADT volume of exit ramp (veh/day);

$AADT_f$ = one-directional AADT volume of freeway in speed-change lane site (including vehicles in the HO lane) (veh/day); and

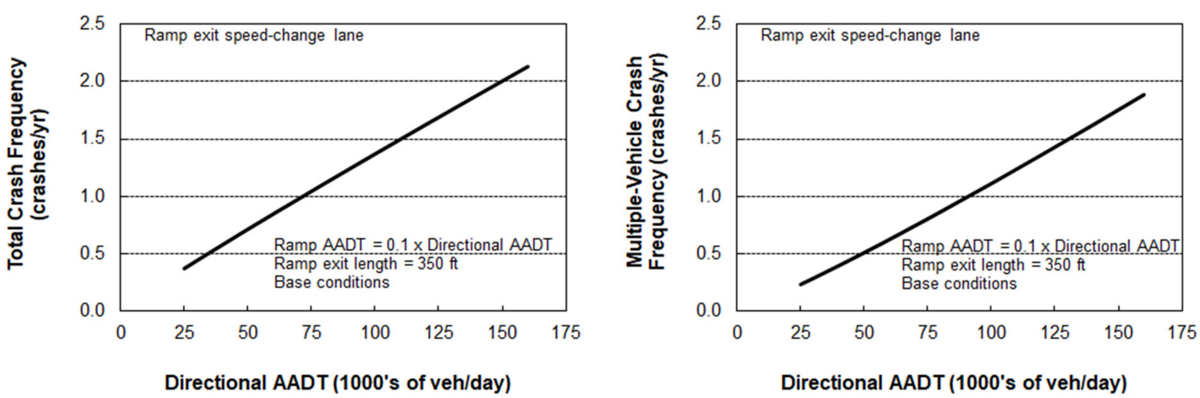
$L_{s,ex}$ = length of ramp exit speed-change lane site (≤ length of ramp exit speed-change lane, as measured from gore point to taper point) (mi).

The length of the ramp exit speed-change lane L_{ex} is shown in Figure 3. The length of the subject speed-change lane site being evaluated $L_{s,ex}$ can equal length L_{ex}. However, $L_{s,ex}$ may be less than length L_{ex} if needed to comply with the segmentation guidelines described in Section 2.6.2.

The SPF coefficients and the overdispersion parameter coefficients are provided in Table 22. The SPFs are illustrated in Figure 14.

Table 22. SPF coefficients for ramp exit speed-change lanes.

	SPF Coefficient			Overdispersion Parameter Coefficient	
Crash Type (*y*)	*a*	*b*	*e*	*c*	*d*
All crash types (*at*)	–8.332	0.939	0.0703	–2.631	–0.706
Multiple vehicle (*mv*)	–10.809	1.123	0.0895	–2.429	–0.667



a. Total Crash Frequency (all crash types) **b. Multiple-Vehicle Crash Frequency**

Figure 14. Graphical form of the SPFs for ramp exit speed-change lanes.

The value of the overdispersion parameter associated with the SPFs for ramp exit speed-change lane sites is determined as a function of site length. This value is computed using Equation 38.

$$k_{ex,ac,y,as} = \exp(c) \times \left(L_{s,ex}\right)^d \tag{38}$$

where

$k_{ex,ac,y,as}$ = overdispersion parameter for ramp exit speed-change lane sites with any cross section *ac*, crash type *y* (*y* = *mv*: multiple vehicle, *at*: all types), and all severities *as*.

2.8.2 SPF Adjustment Factors for Speed-Change Lanes with HOV or HOT Lanes

The AFs for geometric design and traffic control features of speed-change lane sites are presented in this section. Several AFs described in this section include a variable defining the proportion of the site's length along which a particular feature (e.g., median barrier) is present. Guidance is offered herein for computing each proportion. The concept underlying this guidance is that the computed proportion should equal the total length of the feature divided by the length of the site.

$AF_{1,w,ac,y,as}$—Lateral Separation and Access Type

Four AFs are used to describe the relationship between HO lane lateral separation, HO lane access type, and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is lane line separation and continuous access. The AFs for lateral separation and access type are described using the following equation:

$$AF_{1,w,ac,y,as} = \exp\left(a + b \times W_{\text{buffer}} + c \times \frac{X_{DA}}{n_{GPL}}\right) \quad (39)$$

where

$AF_{1,w,ac,y,as}$ = adjustment factor for lateral separation and access type at a speed-change lane site; for site type w (w = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type y, and all severities *as*;

W_{buffer} = width of the buffer between the HO lane and inside GP through lane (ft);

X_{DA} = distance between the last egress point of the HO lane and the gore point of the next exit ramp (mi); and

n_{GPL} = number of GP through lanes in the subject travel direction (lanes).

The coefficients for Equation 39 is provided in

Table 23. As indicated by this table, buffer width has an effect on the AF value only if the lateral separation is "flush buffer." Hence, this width is needed only if flush buffer separation is present and, when it is needed, it is limited to a value in the range of 1.0 to 12.0 feet.

Table 23. Coefficients for lateral separation and access type AF—speed-change lanes.

Lateral Separation	Access Type	Crash Type (y)	AF Coefficients a	AF Coefficients b	AF Coefficients c
Lane line	Continuous	All crash types (at)	0.0	0.0	0.0
		Multiple vehicle (mv)	0.0	0.0	0.0
	At-grade entrance and exit zones	All crash types (at)	0.0	0.0	−0.326
		Multiple vehicle (mv)	0.0	0.0	−0.409
Flush buffer	At-grade entrance and exit zones	All crash types (at)	0.215	−0.0622	−0.326
		Multiple vehicle (mv)	0.164	−0.0588	−0.409
Pylon buffer	At-grade entrance and exit zones	All crash types (at)	−0.234	0.0	−0.326
		Multiple vehicle (mv)	−0.229	0.0	−0.409
Barrier	At-grade entrance and exit zones	All crash types (at)	−0.234	0.0	−0.326
		Multiple vehicle (mv)	−0.229	0.0	−0.409

Also as indicated by

Table 23, the distance X_{DA} has an effect on AF value only if HO lane access is provided via at-grade entrance and exit zones. Moreover, this term of the AF is only applicable if the subject site begins and ends within the distance X_{DA} [i.e., an X_{DA} value of 0.0 is used if (a) the HO lane has continuous access, (b) the site ends before or at the egress point, or (c) the site starts at or after the gore point]. The AF is applicable to "$X_{DA}/\ n_{GPL}$" ratios that range from 0.0 to 0.25 miles per lane. If the computed ratio exceeds 0.25, it should be set to 0.25 when used to compute the AF value.

Details regarding the measurement of the variables associated with this AF are provided in Section 2.5.2.

$AF_{2,w,ac,y,as}$—Inside Shoulder Width

Four AFs are used to describe the relationship between average inside shoulder width and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is a 2-ft inside shoulder width. The AFs are described using the following equation:

$$AF_{2,w,ac,y,as} = \exp(a \times [W_{is} - 2]) \tag{40}$$

where

$AF_{2,w,ac,y,as}$ = adjustment factor for inside shoulder width at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*; and

W_{is} = paved inside shoulder width (ft).

The coefficient for Equation 40 is provided in Table 24. The AF is applicable to inside shoulder widths in the range of 1 to 14 ft.

Table 24. Coefficients for inside shoulder width AF—speed-change lanes.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{2,w,ac,at,as}$	–0.0191
	Multiple vehicle (*mv*)	$AF_{2,w,ac,mv,as}$	–0.0210

$AF_{3,w,ac,y,as}$—Outside Shoulder Width

Four AFs are used to describe the relationship between average outside shoulder width and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);

- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is a 10-ft outside shoulder width. The AFs are described using the following equation:

$$AF_{3,w,ac,y,as} = \exp(a \times [W_s - 10]) \quad (41)$$

where

$AF_{3,w,ac,y,as}$ = adjustment factor for outside shoulder width at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*; and

W_s = paved outside shoulder width (ft).

The coefficient for Equation 41 is provided in Table 25. The AF is applicable to outside shoulder widths in the range of 1 to 14 ft.

Table 25. Coefficients for outside shoulder width AF—speed-change lanes.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{3,w,ac,at,as}$	–0.00686
	Multiple vehicle (*mv*)	$AF_{3,w,ac,mv,as}$	–0.00699

$AF_{4,w,ac,y,as}$—Median Width

Four AFs are used to describe the relationship between median width and predicted crash frequency. The SPFs to which they apply are identified in the following lists:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is a 22-ft median width. The AFs are described using the following equation:

$$AF_{4,w,ac,y,as} = \exp(a \times [W_m - 22]) \quad (42)$$

where

$AF_{4,fs,ac,y,as}$ = adjustment factor for median width at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*; and

W_m = median width (ft).

The coefficient for Equation 42 is provided in Table 26. The AF is applicable to median widths in the range of 4 to 120 ft. Details regarding the measurement of median width are provided in Section 2.5.2.

Table 26. Coefficients for median width AF—speed-change lanes.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{4,w,ac,at,as}$	–0.00162
	Multiple vehicle (*mv*)	$AF_{4,w,ac,mv,as}$	–0.00173

$AF_{5,w,ac,y,as}$—Median Barrier

Four AFs are used to describe the relationship between median barrier presence and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is "no barrier present in the median." The AFs are described using the following equation:

$$AF_{5,w,ac,y,as} = (1.0 - P_{ib}) \times 1.0 + P_{ib} \times \exp(a) \quad (43)$$

with

$$P_{ib} = \frac{L_{ib}}{L_{s,w}} \tag{44}$$

where

$AF_{5,w,ac,y,as}$ = adjustment factor for median barrier at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*;

P_{ib} = proportion of site length with a barrier present in the median (i.e., inside);

L_{ib} = length of lane paralleled by inside (median) barrier (mi); and

$L_{s,w}$ = length of speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane) (mi).

The coefficient for Equation 43 is provided in Table 27. This AF is applicable to cable barrier, concrete barrier, guardrail, and bridge rail.

Table 27. Coefficients for median barrier AF—speed-change lanes.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{5,w,ac,at,as}$	0.231
	Multiple vehicle (*mv*)	$AF_{5,w,ac,mv,as}$	0.290

$AF_{6,w,ac,at,as}$—Outside Barrier

Two AFs are used to describe the relationship between outside barrier presence and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*); and
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*).

The base condition is "no barrier present in the clear zone." The AFs are described using the following equation:

$$AF_{6,w,ac,at,as} = (1.0 - P_{ob}) \times 1.0 + P_{ob} \times \exp(-0.0481) \tag{45}$$

with

$$P_{ob} = \frac{L_{ob}}{L_{s,w}} \tag{46}$$

where

$AF_{6,w,ac,at,as}$ = adjustment factor for outside (roadside) barrier at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, all crash types *at*, and all severities *as*;

P_{ob} = proportion of site length with a barrier present on the outside (roadside);

L_{ob} = length of lane paralleled by outside (roadside) barrier (mi); and

$L_{s,w}$ = length of speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane) (mi).

This AF is applicable to cable barrier, concrete barrier, guardrail, and bridge rail.

$AF_{8,w,ac,y,as}$—Average Speed Differential

Four AFs are used to describe the relationship between the "average speed differential" and predicted crash frequency. This differential represents the difference between the average speed of the inside GP lane and the average speed of the HO lane(s). The SPFs to which the AFs apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is an average speed differential of 0.0 mi/h. The AFs are described using the following equation:

$$AF_{8,w,ac,y,as} = \exp(a \times \Delta_v) \tag{47}$$

where

$AF_{8,w,ac,y,as}$ = adjustment factor for average speed differential at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*; and

Δ_v = average speed differential between the inside GP lane and the HO lane(s) (= speed in HO lane minus speed in GP lane) (mi/h).

The coefficients for Equation 47 are provided in Table 28. As indicated by this table, the average speed differential has an effect on the AF value only if the lateral separation is "continuous" or "flush buffer." Hence, the speed differential variable Δ_v is needed only if continuous or flush buffer separation is present and, when it is needed, it is limited to a value in the range of 0.0 to 15 mi/h.

Table 28. Coefficients for average speed differential AF—speed-change lanes.

Lateral Separation	Access Type	Crash Type (*y*)	AF Coefficient (*a*)
Lane line	Continuous	All crash types (*at*)	0.0232
		Multiple vehicle (*mv*)	0.0261
	At-grade entrance and exit zones	All crash types (*at*)	0.0232
		Multiple vehicle (*mv*)	0.0261
Flush buffer	At-grade entrance and exit zones	All crash types (*at*)	0.0232
		Multiple vehicle (*mv*)	0.0261
Pylon buffer	At-grade entrance and exit zones	All crash types (*at*)	0.0
		Multiple vehicle (*mv*)	0.0
Barrier	At-grade entrance and exit zones	All crash types (*at*)	0.0
		Multiple vehicle (*mv*)	0.0

Details regarding the measurement of speed differential are provided in Section 2.5.2. An equation is provided in that section for estimating a default speed differential value when conditions do not permit its measurement for the subject segment.

$AF_{10,w,ac,y,as}$—Number of HO Lanes

Four AFs are used to describe the relationship between the number of HO lanes and predicted crash frequency. The SPFs to which they apply are identified in the following list:

- SPF for all severities, all crash types, any number of lanes, ramp entrance (*en, ac, at, as*);
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp entrance (*en, ac, mv, as*);
- SPF for all severities, all crash types, any number of lanes, ramp exit (*ex, ac, at, as*); and
- SPF for all severities, multiple-vehicle crashes, any number of lanes, ramp exit (*ex, ac, mv, as*).

The base condition is the presence of one HO lane. The AFs are described using the following equation:

$$AF_{10,w,ac,y,as} = \exp(a \times I_{\geq 2HOL}) \quad (48)$$

where

$AF_{10,w,ac,y,as}$ = adjustment factor for number of HO lanes at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y*, and all severities *as*; and

$I_{\geq 2HOL}$ = indicator variable for the number of HO lanes (= 1.0 if two or more HO lanes present, 0.0 otherwise).

The coefficients for Equation 48 are provided in Table 29. This AF is applicable to sites with one to four HO lanes.

Table 29. Coefficients for number of HO lanes AF—speed-change lanes.

Cross Section (*x*)	Crash Type (*y*)	AF Variable	AF Coefficient (*a*)
Any cross section (*ac*)	All crash types (*at*)	$AF_{10,w,ac,at,as}$	0.293
	Multiple vehicle (*mv*)	$AF_{10,w,ac,mv,as}$	0.261

2.8.3 Severity Distribution for Speed-Change Lanes with HOV or HOT Lanes

The severity distribution for speed-change lane sites is presented in this section. The severity distribution is used in the predictive model to estimate the average crash frequency for the following severity levels: fatal *K*, incapacitating injury *A*, non-incapacitating injury *B*, possible injury *C*, and property-damage-only *PDO*.

The severity distribution proportions are computed using a severity distribution function (SDF). The SDF was developed as a logistic regression model using observed crash data. The SDF, like all regression models, estimates the distribution value as a function of a set of independent variables. The independent variables include various geometric design and traffic control features.

There is one SDF associated with each severity level *j* in the predictive model. The SDF for level *j* predicts the proportion of crashes with severity level *j*, based on various geometric design and traffic control features at the subject site. The SDF also contains a calibration factor that is used to calibrate the SDF to local conditions.

The distribution value for severity level *j* is multiplied by the total crash frequency (all severities) to obtain the total crash frequency for the specified severity level. Similarly, the distribution value can be multiplied by the multiple-vehicle crash frequency or the single-vehicle crash frequency to obtain the predicted crash frequency for a specific crash type and severity level. The predicted average crash frequency is obtained from Equation 6, Equation 7, or Equation 9 as a predicted value. The expected value equivalent should be used if the EB Method is applied.

The general model form of the severity distribution prediction equation for speed-change lane sites is shown in the following equation.

$$N_{p,w,ac,y,j} = N_{p,w,ac,y,as} \times P_{w,ac,at,j} \quad (49)$$

where

$N_{p,w,ac,y,j}$ = predicted average crash frequency of a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and severity level *j* (*j* = *K*: fatal, *A*: incapacitating injury, *B*: non-incapacitating injury, *C*: possible injury, *PDO*: property-damage-only) (crashes/yr);

$N_{p,w,ac,y,as}$ = predicted average crash frequency of a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle, *at*: all types), and all severities *as* (crashes/yr); and

$P_{w,ac,at,j}$ = proportion of crashes with severity level *j* (*j* = *K*: fatal, *A*: incapacitating injury, *B*: non-incapacitating injury, *C*: possible injury, *PDO*: property-damage-only) for all crash types *at* on site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane) with any cross section *ac*.

The SDFs for speed-change lane sites are described by the following equations.

$$P_{w,ac,at,K} = \frac{\exp(V_{w,K+A})}{\frac{1.0}{C_{sdf,w}} + \exp(V_{w,K+A}) + \exp(V_{w,B}) + \exp(V_{w,C})} \times P_{K|K+A,w,ac,at} \quad (50)$$

$$P_{w,ac,at,A} = \frac{\exp(V_{w,K+A})}{\frac{1.0}{C_{sdf,w}} + \exp(V_{w,K+A}) + \exp(V_{w,B}) + \exp(V_{w,C})} \times (1.0 - P_{K|K+A,w,ac,at}) \quad (51)$$

$$P_{w,ac,at,B} = \frac{\exp(V_{w,B})}{\frac{1.0}{C_{sdf,w}} + \exp(V_{w,K+A}) + \exp(V_{w,B}) + \exp(V_{w,C})} \quad (52)$$

$$P_{w,ac,at,C} = \frac{\exp(V_{w,C})}{\frac{1.0}{C_{sdf,w}} + \exp(V_{w,K+A}) + \exp(V_{w,B}) + \exp(V_{w,C})} \quad (53)$$

$$P_{w,ac,at,PDO} = 1.0 - (P_{w,ac,at,K} + P_{w,ac,at,A} + P_{w,ac,at,B} + P_{w,ac,at,C}) \quad (54)$$

where

$V_{w,j}$ = systematic component of crash severity likelihood for severity level *j* at a speed-change lane site with site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane);

$P_{K|K+A,w,ac,at}$ = probability of a fatal *K* crash given that the crash has a severity of either fatal or incapacitating injury *A* for all crash types *at* at a speed-change lane site with site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane); and

$C_{sdf,w}$ = calibration factor to adjust SDF for local conditions at a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane, *ex*: ramp exit speed-change lane).

The first term of Equation 50 and Equation 51 estimates the probability of a fatal or incapacitating injury crash. The second term of Equation 50 (i.e., $P_{K|K+A,w,ac,at}$) is used to convert the estimate into the probability of a fatal crash. A value of 0.209 is used for $P_{K|K+A,en,ac,at}$ and for $P_{K|K+A,ex,ac,at}$ based on an analysis of fatal and incapacitating injury crashes on speed-change lanes with HO lanes.

Ramp Entrance Speed-Change Lanes

A model for estimating the systematic component of crash severity for ramp entrance speed-change lanes is described by the following equation.

$$V_{en,j} = a + \left(b \times \ln\left[AADT_f\right]\right) + (c \times I_{65}) + (d \times I_{70}) + (e \times I_{\geq 3GPL}) + \left(f \times I_{\text{at-grade}}\right) + (g \times P_{ob}) \\ +(h \times P_{ib}) + (i \times I_{R24}) + (j \times I_{\text{flush}}) + (k \times I_{\text{flush}} \times W_{\text{buffer}}) + (l \times P_c) + (m \times P_{hvh}) \\ +\left(p \times X_{e,ext}\right) + (q \times \ln[AADT_{en}]) + \left(r \times \ln\left[AADT_{e,ext}\right]\right) \quad (55)$$

where

$AADT_f$ = one-directional AADT volume of freeway in speed-change lane site (including vehicles in the HO lane) (veh/day);

I_{65} = 65mi/h speed limit indicator variable (= 1.0 if speed limit is 65 mi/h, 0.0 otherwise);

I_{70} = 70mi/h speed limit indicator variable (= 1.0 if speed limit is 70 mi/h, 0.0 otherwise);

$I_{\geq 3GPL}$ = 3 to 7 GP lanes indicator variable (= 1.0 if 3 or more GP lanes, 0.0 otherwise);

$I_{\text{at-grade}}$ = HO lane access type indicator variable (= 1.0 if HO lane access in vicinity of subject site has at-grade entrance and exit zones, 0.0 otherwise);

P_{ob} = proportion of segment length with a barrier present on the outside (roadside);

P_{ib} = proportion of segment length with a barrier present in the median (i.e., inside);

I_{R24} = HO lane access restriction indicator variable (= 1.0 if full-time HO lane, 0.0 otherwise);

I_{flush} = lateral separation indicator variable (= 1.0 if HO lane is separated from the GP lane by a flush buffer, 0.0 otherwise);

W_{buffer} = width of the buffer between the HO lane and inside GP through lane (ft);

P_c = proportion of segment length with a horizontal curve;

P_{hvh} = proportion of hours where volume exceeds 1,000 veh/h/ln;

$X_{e,ext}$ = distance from segment end milepost to nearest downstream exit ramp gore point (mi);

$AADT_{en}$ = AADT volume of entrance ramp (veh/day);

$AADT_{e,ext}$ = AADT volume of exit ramp located at distance $X_{e,ext}$ downstream of the subject segment (veh/day); and

a, b,…, q, r = regression coefficients.

The SDF coefficients in Equation 55 are provided in Table 30.

Table 30. SDF coefficients for ramp entrance speed-change lanes.

SDF Coefficient	Coefficient Value by Severity Level *j*		
	Fatal or Incapacitating Injury (*K*+*A*)	Non-Incapacitating Injury (*B*)	Possible Injury (*C*)
a	5.207	3.946	2.238
b	-0.728	-0.552	-0.286
c	0.748	0.411	0.0
d	0.803	0.474	0.0
e	0.586	0.430	0.0
f	–0.308	–0.308	–0.154
g	–0.104	0.0	0.0
h	–0.0989	0.0	0.0
i	0.185	0.102	0.0
j	–0.447	–0.281	–0.123
k	0.0374	0.0285	0.0
l	0.0306	0.0306	0.0
m	–0.199	–0.199	0.104
p	–0.0598	–0.0598	–0.0538
q	–0.0762	–0.0524	0.0
r	–0.0789	0.0	0.0

The posted speed limit is limited to 60, 65, and 70 mi/h. The number of GP lanes is limited to a range of 2 to 7.

The variable P_{ob} is computed as the ratio of the length of lane paralleled by outside (roadside) barrier divided by the length of the site (as shown in Equation 46). Similarly, the variable P_{ib} is computed as the ratio of the length of lane paralleled by inside (median) barrier divided by the length of the site (as shown in Equation 44).

Buffer width is needed only if flush buffer separation is present and, when it is needed, it is limited to a value in the range of 1.0 to 12.0 feet.

The variable P_c is computed as the ratio of the length of horizontal curve in the site divided by the length of the site.

The proportion of hours in the average day where the volume exceeds 1,000 veh/h/ln P_{hvh} is computed using the average hourly volume distribution associated with the subject site. This distribution will typically be computed using the data obtained from the continuous traffic counting station that (a) is nearest to the subject freeway and (b) has similar traffic demand and peaking characteristics. The SDF is applicable to P_{hvh} values in the range of 0.0 to 0.766. Additional discussion of this variable is provided in Section 2.7.2 for the High-Volume Hours AF.

The $X_{e,ext}$ and $AADT_{e,ext}$ variables describe the distance to (and volume of) the nearest downstream exit ramp. Only those ramps that contribute volume to the subject segment are of interest. Hence, a downstream entrance ramp is not of interest. For similar reasons, an upstream exit ramp is not of interest. If the ramp does not exist or it is located more than 2.0 mi from the segment, then the distance $X_{e,ext}$ can be set to 2.0 mi in the model to obtain the correct results.

The sign of a coefficient in Table 30 indicates the direction of the change in the proportion of crashes associated with a change in the corresponding variable. For example, the negative coefficient associated with coefficient *b* indicates that the proportion of fatal *K* crashes decreases with an increase in volume. A similar trend is indicated for barrier presence on incapacitating injury *A*, non-incapacitating injury *B*, and possible injury *C* crashes. By inference, the proportion of property-damage-only *PDO* crashes *increases* with an increase in volume.

Ramp Exit Speed-Change Lanes

A model for estimating the systematic component of crash severity for ramp exit speed-change lanes is described by the following equation.

$$\begin{aligned} V_{ex,j} = {} & a + (b \times \ln[AADT_f]) + (c \times I_{65}) + (d \times I_{70}) + (e \times I_{\geq 3GPL}) + (f \times I_{\text{at-grade}}) + (g \times P_{ob}) \\ & + (h \times P_{ib}) + (i \times I_{R24}) + (j \times I_{\text{flush}}) + (k \times I_{\text{flush}} \times W_{\text{buffer}}) + (l \times P_c) + (m \times P_{hvh}) \\ & + (n \times X_{b,ent}) + (q \times \ln[AADT_{b,ent}]) + (r \times \ln[AADT_{ex}]) \end{aligned} \quad (56)$$

where

$AADT_f$ = one-directional AADT volume of freeway in speed-change lane site (including vehicles in the HO lane) (veh/day);

I_{65} = 65mi/h speed limit indicator variable (= 1.0 if speed limit is 65 mi/h, 0.0 otherwise);

I_{70} = 70mi/h speed limit indicator variable (= 1.0 if speed limit is 70 mi/h, 0.0 otherwise);

$I_{\geq 3GPL}$ = 3 to 7 GP lanes indicator variable (= 1.0 if 3 or more GP lanes, 0.0 otherwise);

$I_{\text{at-grade}}$ = HO lane access type indicator variable (= 1.0 if HO lane access in vicinity of subject site has at-grade entrance and exit zones, 0.0 otherwise);

P_{ob} = proportion of segment length with a barrier present on the outside (roadside);

P_{ib} = proportion of segment length with a barrier present in the median (i.e., inside);

I_{R24} = HO lane access restriction indicator variable (= 1.0 if full-time HO lane, 0.0 otherwise);

I_{flush} = lateral separation indicator variable (= 1.0 if HO lane is separated from the GP lane by a flush buffer, 0.0 otherwise);

W_{buffer} = width of the buffer between the HO lane and inside GP through lane (ft);

P_c = proportion of segment length with a horizontal curve;

P_{hvh} = proportion of hours where volume exceeds 1,000 veh/h/ln;

$X_{b,ent}$ = distance from segment begin milepost to nearest upstream entrance ramp gore point (mi);

$AADT_{ex}$ = AADT volume of exit ramp (veh/day);

$AADT_{b,ent}$ = AADT volume of entrance ramp located at distance $X_{b,ent}$ upstream of the subject segment (veh/day);; and

a, b,…, q, r = regression coefficients.

The SDF coefficients in Equation 56 are provided in Table 31.

Table 31. SDF coefficients for ramp exit speed-change lanes.

SDF Coefficient	Coefficient Value by Severity Level *j*		
	Fatal or Incapacitating Injury (*K*+*A*)	Non-Incapacitating Injury (*B*)	Possible Injury (*C*)
a	5.207	3.946	2.238
b	-0.728	-0.552	-0.286
c	0.748	0.411	0.0
d	0.803	0.474	0.0
e	0.586	0.430	0.0
f	–0.308	–0.308	–0.154
g	–0.104	0.0	0.0
h	–0.0989	0.0	0.0
i	0.185	0.102	0.0
j	–0.447	–0.281	–0.123
k	0.0374	0.0285	0.0
l	0.0306	0.0306	0.0
m	–0.199	–0.199	0.104
n	-0.0372	-0.0372	0.0
q	–0.0762	–0.0524	0.0
r	–0.0789	0.0	0.0

The posted speed limit is limited to 60, 65, and 70 mi/h. The number of GP lanes is limited to a range of 2 to 7 lanes.

The variable P_{ob} is computed as the ratio of the length of lane paralleled by outside (roadside) barrier divided by the length of the site (as shown in Equation 46). Similarly, the variable P_{ib} is computed as the ratio of the length of lane paralleled by inside (median) barrier divided by the length of the site (as shown in Equation 44).

Buffer width is needed only if flush buffer separation is present and, when it is needed, it is limited to a value in the range of 1.0 to 12.0 feet.

The variable P_c is computed as the ratio of the length of horizontal curve in the site divided by the length of the site.

The proportion of hours in the average day where the volume exceeds 1,000 veh/h/ln P_{hvh} is computed using the average hourly volume distribution associated with the subject site. This distribution will typically be computed using the data obtained from the continuous traffic counting station that (a) is nearest to the subject freeway and (b) has similar traffic demand and peaking characteristics. The SDF is applicable to P_{hvh} values in the range of 0.0 to 0.766. Additional discussion of this variable is provided in Section 2.7.2 for the High-Volume Hours AF.

The $X_{b,ent}$ and $AADT_{b,ent}$ variables describe the distance to (and volume of) the nearest upstream entrance ramp. Only those ramps that contribute volume to the subject segment are of interest. Hence, a downstream entrance ramp is not of interest. For similar reasons, an upstream exit ramp is not of interest. If the ramp does not exist or it is located more than 2.0 mi from the segment, then the distance $X_{b,ent}$ can be set to 2.0 mi in the model to obtain the correct results.

The sign of a coefficient in Table 31 indicates the direction of the change in the proportion of crashes associated with a change in the corresponding variable. For example, the negative coefficient associated with coefficient *b* indicates that the proportion of fatal *K* crashes decreases with an increase in volume. A similar trend is indicated for barrier presence on incapacitating injury *A*, non-incapacitating injury *B*, and possible injury *C* crashes. By inference, the proportion of property-damage-only *PDO* crashes *increases* with an increase in volume.

2.8.4 Crash Type Distribution for Speed-Change Lanes with HOV or HOT Lanes

The crash type distributions for speed-change lanes are presented in this section. They are used in the predictive model to estimate the average crash frequency for typical crash types.

For ramp entrance speed-change lanes, the two crash frequency estimates that are used to compute the crash type distribution are:

- Multiple-vehicle crashes $N_{p,en,ac,mv,as}$ (from Equation 7); and
- Single-vehicle crashes $N_{p,en,ac,sv,as}$ (from Equation 9).

For ramp exit speed-change lanes, the two crash frequency estimates that are used to compute the crash type distribution are:

- Multiple-vehicle crashes $N_{p,ex,ac,mv,as}$ (from Equation 7 with subscript "*ex*" substituted for "*en*"); and
- Single-vehicle crashes $N_{p,ex,ac,sv,as}$ (from Equation 9 with subscript "*ex*" substituted for "*en*").

The estimates needed to compute the crash type distribution are obtained from the aforementioned equations as predicted values; however, their expected value equivalents should be used if the EB Method is applied.

The general model form of the crash type distribution prediction equation is shown in the following equation.

$$N_{p,w,ac,y(j),as} = N_{p,w,ac,y,as} \times P_{w,ac,y(j),as} \quad (57)$$

where

$N_{p,w,ac,y(j),as}$ = predicted average crash frequency of a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane; *ex*: ramp exit speed-change lane), any cross section *ac*, subtype *j* of crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle), and all severities *as* (crashes/yr);

$N_{p,w,ac,y,as}$ = predicted average crash frequency of a speed-change lane site; for site type *w* (*w* = *en*: ramp entrance speed-change lane; *ex*: ramp exit speed-change lane), any cross section *ac*, crash type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle), and all severities *as* (crashes/yr); and

$P_{w,ac,y(j),as}$ = proportion of crash-type *y* (*y* = *sv*: single vehicle, *mv*: multiple vehicle) that are subtype *j* (*j* = rear end, head on, etc.) and all severities *as* on site type *w* (*w* = *en*: ramp entrance speed-change lane; *ex*: ramp exit speed-change lane) with any cross section *ac*.

Each application of Equation 57 requires one crash type distribution value (i.e., proportion) for each crash subtype *j*. These values are shown in Table 32.

Table 32. Default distribution of crash type for speed-change lanes.

		Proportion of Crashes by Site Type	
Crash Type Category	**Crash Type (*j*)**	**Ramp Entrance**	**Ramp Exit**
Multiple-vehicle	Head-on	0.004	0.003
	Right-angle	0.034	0.032
	Rear-end	0.661	0.682
	Sideswipe	0.235	0.202
	Other multiple-vehicle crashes	0.066	0.081
	Total:	1.000	1.000
Single-vehicle	Crash with animal	0.005	0.006
	Crash with fixed object	0.775	0.777
	Crash with other object	0.120	0.163
	Crash with parked vehicle	0.001	0.000
	Other single-vehicle crashes	0.099	0.054
	Total:	1.000	1.000

2.9 CALIBRATION OF THE SPFs AND SDFs TO LOCAL CONDITIONS

Crash frequencies, even for nominally similar freeway segments or speed-change lane sites, can vary widely from one jurisdiction to another. Geographic regions differ markedly in climate, animal population, driver populations, crash-reporting threshold, and crash-reporting practices. These variations may result in some jurisdictions experiencing a different number of traffic crashes on freeways than others. Calibration factors are included in the methodology to allow transportation agencies to adjust the SPFs and SDFs to match actual local conditions. The calibration procedures for SPFs and SDFs are presented in the appendix for Part C of the HSM (*4*) and the appendix to the 2014 HSM Supplement (*2*), respectively.

Default values are provided for the crash type distributions used in the methodology. These values can also be replaced with locally derived values. The derivation of local values is addressed in the appendix for Part C of the HSM (4).

Calibration is performed separately for each predictive model equation described in this chapter. Table 33 identifies the combinations of site type and crash type represented in each predictive model equation and for which calibration factors can be derived. Similarly, Table 34 identifies the combinations represented in each severity distribution function (SDF) and for which calibration factors can be derived. Note that there are only three unique SDF calibration factors shown in this table (i.e., the same factor is used for all severity levels of a given site type).

The sites selected to quantify any one of the calibration factors listed in Table 33 or Table 34 should equal or exceed the minimum site sample size needed for local calibration. This minimum number is specified in the appendix for Part C of the HSM (*4*).

Table 33. Crash frequency predictive models with a calibration factor.

Site Type (w)	Crash Type (y)	Crash Severity (z)	Calibration Factor	
			Symbol	Equation
Freeway segment (*fs*)	All crash types (*at*)	All severities (*as*)	$C_{fs,ac,at,as}$	Equation 2
	Multiple vehicle (*mv*)	All severities (*as*)	$C_{fs,ac,mv,as}$	Equation 4
Ramp entrance speed-change lane (*en*)	All crash types (*at*)	All severities (*as*)	$C_{en,ac,at,as}$	Equation 6
	Multiple vehicle (*mv*)	All severities (*as*)	$C_{en,ac,mv,as}$	Equation 8
Ramp exit speed-change lane (*ex*)	All crash types (*at*)	All severities (*as*)	$C_{ex,ac,at,as}$	see note [a]
	Multiple vehicle (*mv*)	All severities (*as*)	$C_{ex,ac,mv,as}$	see note [a]

a – The equations for ramp exit speed-change lanes are not shown. However, these equations are the same as Equation 6 and Equation 8 except that the subscript "*ex*" is substituted for "*en*" in each variable.

Table 34. Severity distribution functions with a calibration factor.

Site Type (w)	Crash Type (y)	Crash Severity (z)	Calibration Factor	
			Symbol	Equation
Freeway segment (*fs*)	All crash types (*at*)	Fatal (*K*)	$C_{sdf,fs}$	Equation 28
		Incapacitating injury (*A*)	$C_{sdf,fs}$	Equation 29
		Non-incapacitating injury (*B*)	$C_{sdf,fs}$	Equation 30
		Possible injury (*C*)	$C_{sdf,fs}$	Equation 31
Ramp entrance speed-change lane (*en*)	All crash types (*at*)	Fatal (*K*)	$C_{sdf,en}$	Equation 50
		Incapacitating injury (*A*)	$C_{sdf,en}$	Equation 51
		Non-incapacitating injury (*B*)	$C_{sdf,en}$	Equation 52
		Possible injury (*C*)	$C_{sdf,en}$	Equation 53
Ramp exit speed-change lane (*ex*)	All crash types (*at*)	Fatal (*K*)	$C_{sdf,ex}$	Equation 50
		Incapacitating injury (*A*)	$C_{sdf,ex}$	Equation 51
		Non-incapacitating injury (*B*)	$C_{sdf,ex}$	Equation 52
		Possible injury (*C*)	$C_{sdf,ex}$	Equation 53

The sites used to calibrate the predictive models must be obtained from urban freeways with HOV or HOT lanes that have one or more of the design configurations identified in the following list:

- Lane line lateral separation with continuous access or with limited access via at-grade entrance/exit zones.
- Flush buffer lateral separation with limited access via at-grade entrance/exit zones.
- Pylon buffer lateral separation with limited access via at-grade entrance/exit zones.
- Barrier separation with limited access via at-grade entrance/exit zones.

One set of the calibration factors listed in Table 33 and Table 34 can be developed for any combination of the design configurations identified in the previous bullet list. However, if desired, one set of factors may be developed for each of the four design configurations and then used when applying the predictive models to that specific configuration.

In general, the site characteristics data needed to apply the predictive model equations or the SDFs should be acquired for each site in the calibration database. However, if information on speed limit is not available, then an assumed value can be substituted (where the substituted value is based on agency policy or typical practice). If data are not available to compute the "proportion of hours where volume exceeds 1,000 veh/h/ln," then a default value (computed with Equation 12) can be used to calibrate the models. Similarly, if data are not available to compute the "average speed differential" then a default value (computed with Equation 13) can be used to calibrate the models.

2.10 LIMITATIONS OF PREDICTIVE METHOD

This section discusses limitations of the predictive models described in this chapter. The predictive method does not account for the influence of the following conditions on crash potential:

- Freeways in rural areas
- Freeways with managed lanes other than HOV or HOT lanes (e.g., truck-restricted lanes, truck-only lanes, or bus-only lanes)
- Freeways with eight or more GP through lanes in the subject travel direction
- Freeways where HOV or HOT lanes are accommodated (a) a separate roadway, (b) a reversible lane, or (c) a contraflow lane.
- Freeways with concurrent HOV or HOT lanes with a flush buffer and continuous access.
- Freeways with HOV or HOT lanes that are accessed by grade-separated entrance/exit points.
- Freeways with part-time shoulder use or bus-on-shoulder operation.
- Shoulder rumble strip presence
- Ramp metering
- Toll plazas
- Work zone presence
- Speed-change lanes that provide left-side access to the freeway

The predictive method does not distinguish between barrier types (i.e., cable barrier, concrete barrier, guardrail, and bridge rail) in terms of their possible unique influence on crash severity.

2.11 APPLICATION OF PREDICTIVE METHOD

The predictive method presented in this chapter is applied to a freeway facility by following the 18 steps presented in Section 2.5. All computations of average crash frequency are conducted with values expressed to three decimal places. This level of precision is needed only for consistency in computations. In the last stage of computations, rounding the final estimates of average crash frequency to one decimal place is appropriate.

2.11.1 Freeways with Toll Facilities

The predictive method can be used to evaluate a freeway section that is part of toll facility provided that the section is sufficiently distant from the toll plaza that the plaza does not influence vehicle operation. The predictive method is not directly applicable to any portion of the freeway that (a) is in the immediate vicinity of a toll plaza, (b) is widened to accommodate vehicle movements through the toll plaza, (c) experiences toll-related traffic queues, or (d) experiences toll-related speed changes.

2.11.2 Evaluation of Freeway Facilities without HOV or HOT Lanes

When evaluating some freeway facilities with HOV or HOT lanes, it may be useful to evaluate a one-directional site that does not have HO lanes. Two cases are described in the following paragraphs and guidance is provided for using the method described in Chapter 18 of the HSM Supplement (*2*) to evaluate the one-directional site that does not have HO lanes.

Case A. HO Lanes in Only One Direction

For this case, the freeway facility of interest has one or more HO lanes in one travel direction but not in the other travel direction. In this situation, the predictive method described in this chapter can be used to evaluate the travel direction that provides the HO lanes and the method described in Chapter 18 of the HSM Supplement (*2*) can be used to evaluate the opposing travel direction that does not have HO lanes.

Case B. Existing Freeway Does Not Have HO Lanes

For this case, the travel direction of interest for an existing freeway facility does not have an HO lane but a proposed alternative is to include one or more HO lanes. In this situation, the predictive method described in this chapter can be used to evaluate the proposed alternative and the method described in Chapter 18 of the HSM Supplement (*2*) can be used to evaluate the existing condition.

Procedure

The process for applying the two predictive methods is described in the following paragraphs. *When implementing this process, all predictive models used must be calibrated for the region in which the subject freeway facility is located.*

Chapter 18 of the HSM Supplement (*2*) includes predictive models for one-directional speed-change lane sites and for two-directional freeway segments. As a result, the predictive models for speed-changes lane sites in Chapter 18 are directly applicable to the evaluation of one travel direction of a freeway. In contrast, the predictive models for freeway segments in Chapter 18 are based on the evaluation of two-directional freeway segments. The guidance in the following steps can be used to evaluate a one-directional segment using the two-directional models in Chapter 18.

1. *Define project limits and study period*— Complete Steps 1 and 2 of the predictive method described in Chapter 18, Section 18.4.1. The project limits and study period for the freeway facility without HO lanes must be the same as those used for the freeway facility with HO lanes.

2. *Determine the two-directional AADT*— Complete Step 3 of the predictive method described in Chapter 18. For Case A, the two-directional AADT needed for the Chapter 18 freeway segment SPF equals twice the AADT for the opposing travel direction. For Case B, the two-directional AADT needed for the Chapter 18 freeway segment model equals twice the AADT for the for the subject direction of travel for the existing freeway.

3. *Obtain site characteristics*— Complete Step 4 of the predictive method described in Chapter 18. For Case A, the variables used in the SPF adjustment factors (i.e., CMFs) in Chapter 18 are based on measurements for the opposing travel direction. All variables are measured for the opposing direction of travel and considered to be the same for the freeway on the other side of the centerline. For example, the freeway segment SPF selected for use from Chapter 18 is based on twice the number of through lanes serving the opposing travel direction.

   For Case B, the variables used in the CMFs in Chapter 18 are based on measurements for the subject direction of travel for the existing freeway. All variables are measured for the subject direction of travel and considered to be the same for the freeway on the other side of the centerline. For example, the freeway segment SPF selected for use from Chapter 18 is based on twice the number of through lanes serving the subject direction of travel for the existing freeway.

4. *Divide the two-directional freeway into sites*— Complete Step 5 of the predictive method described in Chapter 18. For Case A, use only the characteristics of the opposing direction of travel to segment the freeway. Then, a two-directional freeway segment is created by assuming it to be symmetrical about the freeway centerline with the "other" side of the freeway mirroring the opposing direction of travel. Thus, if the opposing direction of travel has a length of 0.50 miles and a downstream ramp exit 0.23 miles from the end of the segment, then the "other" side is also modeled as having a length of 0.50 miles and a downstream ramp exit 0.23 miles from the end of the segment.

   For Case B, use only the characteristics of the subject direction of travel to segment the freeway. Then, a two-directional freeway segment is created by assuming it to be symmetrical about the freeway centerline with the "other" side of the freeway mirroring the subject direction of travel. Thus, if the subject direction of travel has a length of 0.50 miles and a downstream ramp exit 0.23 miles from the end of the segment, then the "other" side is also modeled as having a length of 0.50 miles and a downstream ramp exit 0.23 miles from the end of the segment.

5. *Compute the one-directional predicted crash frequency*— Complete Steps 6 through 12 of the predictive method described in Chapter 18. The two-directional predicted crash frequency obtained from the Chapter 18 freeway segment model is divided by 2 to obtain the predicted crash frequency for the one-directional freeway segment of interest.

6. *Compute the one-directional expected crash frequency*— If the EB method is used, complete Step 13 of the predictive method described in Chapter 18. The observed crashes assigned to the subject one-directional segment are multiplied by 2 (and crashes assigned to the other direction are ignored). The two-directional predicted crash frequency obtained from the Chapter 18 freeway segment model is used to compute the weighted adjustment factor *w* and the expected crash frequency. The expected crash frequency is

then divided by 2 to obtain the expected crash frequency for the subject one-directional freeway segment.

2.12 SUMMARY

The predictive method for freeways is applied by following the 18 steps of the predictive method presented in Section 2.5. It is used to estimate the average crash frequency for a series of contiguous sites, or a single individual site. If a freeway facility is being evaluated, it is divided into a series of sites in Step 5 of the predictive method.

Predictive models are applied in Steps 9, 10, and 11 of the method. Each predictive model typically consists of a safety performance function (SPF), one or more SPF adjustment factors (AFs), a calibration factor, a severity distribution, and a crash type distribution. The SPF is selected in Step 9. It is used to estimate the predicted average crash frequency for a site with base conditions. AFs are selected in Step 10. They are combined with the estimate from the SPF to produce the predicted average crash frequency the subject site.

When observed crash data are available, the EB Method is applied in Step 13 or 15 of the predictive method to estimate the expected average crash frequency. The EB Method can be applied at the site-specific level in Step 13 or at the project level in Step 15. The choice of level will depend on (a) the required reliability of the estimate and (b) the accuracy with which each observed crash can be associated with an individual site.

As an evaluation option, the severity distribution can be selected in Step 13 and used to estimate the average crash frequency for one or more crash severity levels (i.e., fatal, incapacitating injury, non-incapacitating injury, possible injury, or property-damage-only crash). Also as an option, the crash type distribution can be used in Step 13 to estimate the average crash frequency for one or more crash types (e.g., head-on, fixed object).

The SPF should be calibrated to the specific state or geographic region in which the project is located. Calibration accounts for differences in state or regional crash frequencies, relative to the states and regions represented in the data used to define the predictive models described in this chapter. The process for determining calibration factors for the predictive models is described in the appendix for Part C of the HSM (*4*). Section 2.13 presents several sample problems that detail the application of the predictive method.

2.13 SAMPLE PROBLEMS

In this section, two sample problems are presented using the predictive method described in this chapter. The problems are described in Table 35. The NCHRP 17-89A final report provides two additional sample problems.

Note: In the following sample problems, the tables and text show results of calculations copied from a spreadsheet used to obtain these results. In some cases, there are small differences between the results shown and those that may be obtained using a calculator. These differences occur because the results shown in the text were rounded to the third decimal whereas the values from the spreadsheet were not rounded. Additionally, the sample calculations may not show all the results, just selected calculations. Since the worksheets are not included here, some results may be omitted.

Table 35. List of Sample Problems

Problem No.	Description
1	Evaluation of a ramp entrance speed-change lane adjacent to a freeway with a continuous-access HOV lane
2	Evaluation of a freeway segment at which the addition of a continuous-access HOV lane is being considered

2.13.1 SAMPLE PROBLEM 1

The Site/Facility

The urban freeway speed-change lane site of interest has two GP lanes and a continuous access HOV lane in the subject travel direction. The site extends for the length of the speed-change lane. The freeway section and the site of interest are shown in Figure 15.

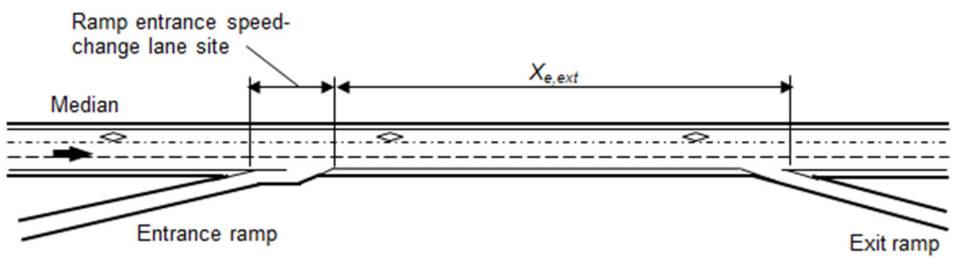


Figure 15. Freeway section and site of interest for sample problem 1.

The Question

What is the predicted average crash frequency of the speed-change lane site for the specified study year?

The Facts

The study period is one year in duration (i.e., Year 2020). The conditions present during this year are provided in the following list:

- 2 GP through lanes
- 1 HOV lane
- 0.14-mi site length (same as the length of the speed-change lane, as measured from gore point to taper point)
- 60-mi/h speed limit
- No horizontal curvature
- 6-ft inside shoulder width (paved)
- 10-ft outside shoulder width (paved)
- 22-ft median width
- Median barrier extends for the length of the site

- No outside (roadside) barrier
- HOV lane is restricted to high-occupancy vehicles 24 hours per day
- Continuous access to and from the HOV lane
- Lane line separation between GP and HOV lanes
- Downstream exit ramp is 0.65 miles from the segment and has an AADT volume of 5400 vehicles per day (i.e., $X_{e,ext}$ = 0.65 mi; $AADT_{e,ext}$ = 5400 veh/day)
- Freeway AADT in subject direction of travel is 54,800 vehicles per day
- Entrance ramp AADT is 5200 vehicles per day
- Calibration factors: $C_{en,ac,at,as}$ = 1.04; $C_{en,ac,mv,as}$ = 1.03; $C_{sdf,en}$ = 1.05

The site is a ramp entrance speed-change lane so the distance to the "upstream" entrance ramp is 0.0 miles and its AADT volume is that of the entrance ramp (i.e., $X_{b,ent}$ = 0.0 mi; $AADT_{b,ent}$ = 5200 veh/day)

Assumptions

- The proportion of hours in the average day where lane volume exceeds 1,000 vehicles per hour per lane is described by the default value obtained from Equation 12. The computed value is 0.40.
- The average speed differential between the inside GP lane and the HO lane is described by the default value obtained from Equation 13. The computed value is 4.1 mi/h.
- The crash type distribution is described by the default values presented in Table 32.

Results

Using the predictive method steps as outlined below, the predicted average total (all crash types and severities) crash frequency for the site of interest is determined to be 2.1 crashes per year, and the predicted average fatal-and-injury crash frequency is determined to be 0.7 crashes per year (rounded to one decimal place).

The sequence of calculations undertaken to obtain these results are described in the following sections.

Steps

Step 1 through 8

The information obtained for steps 1 through 8 are listed in the previous sections. Observed crash data are not obtained because the EB Method will not be applied.

Step 9—For the selected site, determine and apply the appropriate SPF.

The SPF for ramp entrance speed-change lanes (i.e., Equation 35) is used to compute the predicted average crash frequency for base conditions. The site length $L_{s,en}$ is equal to the ramp entrance length L_{en}. The predicted total crash frequency is computed using the following equation.

$$N_{spf,en,ac,at,as} = L_{s,en} \times \exp\left(a + b \times \ln[AADT_f] + e \times \ln[AADT_{en}]\right)$$
$$= 0.14 \times \exp(-8.417 + 0.939 \times \ln[54{,}800] + 0.0703 \times \ln[5200])$$
$$= 1.591 \text{ crashes/yr}$$

Similarly, the SPF for multiple-vehicle crashes is calculated from Equation 35 to yield the following result:

$$N_{spf,en,ac,mv,as} = 1.177 \text{ crashes/yr}$$

Step 10—Multiply the result obtained in Step 9 by the appropriate AFs.
The AFs in the predictive model equation for speed-change lane sites are described in this step.

Lateral Separation and Access Type ($AF_{1,en,ac,y,as}$)
The lateral separation is lane line and the access is continuous, which is the base condition for this AF. Hence, the value of $AF_{1,en,ac,y,as}$ is 1.000 for both total crashes and multiple-vehicle crashes.

Inside Shoulder Width ($AF_{2,en,ac,y,as}$)
The inside shoulder width AF is computed using Equation 40. This equation is repeated below:

$$AF_{2,w,ac,y,as} = \exp(a \times [W_{is} - 2])$$

The subject site has an average inside shoulder width of 6 feet. From Table 24, the coefficient a equals −0.0191 for total crashes. The AF value for total crashes is computed as:

$$AF_{2,en,ac,at,as} = \exp(a \times [6 - 2])$$
$$= 0.926$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{2,en,ac,mv,as} = 0.919$.

Outside Shoulder Width ($AF_{3,en,ac,y,as}$)
The subject site has a 10-ft outside shoulder width, which is the base condition for the outside shoulder width AF. Hence, $AF_{3,en,ac,at,as}$ and $AF_{3,en,ac,mv,as}$ are equal to 1.000.

Median Width ($AF_{4,en,ac,y,as}$)
The subject site has a 22-ft median width, which is the base condition for the median width AF. Hence, $AF_{4,en,ac,at,as}$ and $AF_{4,en,ac,mv,as}$ are equal to 1.000.

Median Barrier ($AF_{5,en,ac,y,as}$)
The median barrier AF is computed using Equation 43. This equation is repeated below:

$$AF_{5,w,ac,y,as} = (1.0 - P_{ib}) \times 1.0 + P_{ib} \times \exp(a)$$

The subject site has median barrier that extends for the length of the site so the proportion P_{ib} equals 1.000. From Table 27, the coefficient a equals 0.231 for total crashes. The AF value for total crashes is computed as:

$$AF_{5,en,ac,at,as} = (1.0 - 1.000) \times 1.0 + 1.000 \times \exp(0.231)$$
$$= 1.260$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{5,en,ac,mv,as}$ = 1.336.

Outside Barrier ($AF_{6,en,ac,at,as}$)

The subject site does not have barrier on the outside (roadside), which is the base condition. Hence, $AF_{6,en,ac,at,as}$ is equal to 1.000. This AF does not apply to multiple-vehicle crashes.

Average Speed Differential ($AF_{8,en,ac,y,as}$)

The average speed differential AF is computed using Equation 47. This equation is repeated below:

$$AF_{8,w,ac,y,as} = \exp(a \times \Delta_v)$$

The subject site has an average speed differential of 4.1 mi/h. From Table 28, the coefficient a equals 0.0232 for total crashes. The AF value for total crashes is computed as:

$$AF_{8,en,ac,at,as} = \exp(0.0232 \times 4.1)$$
$$= 1.100$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{8,en,ac,mv,as}$ = 1.113.

Number of HO Lanes ($AF_{10,en,ac,y,as}$)

The subject site has one HO lane, which is the base condition. Hence, $AF_{10,en,ac,at,as}$ and $AF_{10,en,ac,mv,as}$ are equal to 1.000.

Computed Ramp Entrance Crash Frequency

The AFs are applied to the total crash frequency SPF as follows:

$$N^*_{p,en,ac,at,as}$$
$$= N_{spf,en,ac,at,as} \times \left(AF_{1,en,ac,at,as} \times \ldots \times AF_{6,en,ac,at,as} \times AF_{8,en,ac,at,as} \times AF_{10,en,ac,at,as}\right)$$
$$= 1.591$$
$$\times (1.000 \times 0.926 \times 1.000 \times 1.000 \times 1.260 \times 1.000 \times 1.100 \times 1.000)$$
$$= 1.591 \times 1.284$$
$$= 2.042 \text{ crashes/yr}$$

The AFs are applied to the multiple-vehicle crash frequency SPF as follows:

$$N^*_{p,en,ac,mv,as}$$
$$= N_{spf,en,ac,mv,as} \times \left(AF_{1,en,ac,mv,as} \times \ldots \times AF_{5,en,ac,mv,as} \times AF_{8,en,ac,mv,as} \times AF_{10,en,ac,mv,as}\right)$$
$$= 1.177 \times (1.000 \times 0.919 \times 1.000 \times 1.000 \times 1.336 \times 1.113 \times 1.000)$$
$$= 1.177 \times 1.368$$

$$= 1.610 \text{ crashes/yr}$$

Step 11—Multiply the result obtained in Step 10 by the appropriate calibration factor.
A calibration factor of 1.04 has been determined for the total crash frequency SPF and a calibration of 1.03 has been determined for multiple-vehicle crash frequency SPF. The predicted average total crash frequency is computed as:

$$N_{p,en,ac,at,as} = N^*_{p,en,ac,at,as} \times C_{en,ac,at,as}$$
$$= 2.041 \times 1.04$$
$$= 2.124 \text{ crashes/yr}$$

The unadjusted predicted multiple-vehicle crash frequency is computed as:

$$N'_{p,en,ac,mv,as} = N^*_{p,en,ac,mv,as} \times C_{en,ac,mv,as}$$
$$= 1.610 \times 1.03$$
$$= 1.658 \text{ crashes/yr}$$

Finally, the predicted average multiple-vehicle crash frequency is computed using Equation 7 as follows.

$$N_{p,en,ac,mv,as} = \min\left[N_{p,en,ac,at,as}, N'_{p,en,ac,mv,as}\right]$$
$$= \min[2.124, 1.658]$$
$$= 1.658 \text{ crashes/year}$$

The predicted average single-vehicle crash frequency is calculated using Equation 9 as follows:

$$N_{p,en,ac,sv,as} = N_{p,en,ac,at,as} - N_{p,en,ac,mv,as}$$
$$= 2.124 - 1.658$$
$$= 0.466 \text{ crashes/yr}$$

Step 12—If there is another year to be evaluated in the evaluation period for the selected site, return to Step 8. Otherwise, proceed to Step 13.
The study period is one year (i.e., 2020), so steps 8 through 11 do not need to be repeated for another year.

Step 13—Apply site-specific EB Method (if applicable) and apply crash distributions.
This step consists of three optional sets of calculations—site-specific EB Method, severity distribution, and crash type distribution.

Apply the site-specific EB Method to a future time period, if appropriate.

The site-specific EB Method is not applied in this sample problem.

Apply the severity distribution, if desired.

To apply the SDFs, the systematic component of crash severity likelihood $V_{en,j}$ is computed for each severity level *j* using Equation 55 as follows:

$$V_{en,j} = a + (b \times \ln[AADT_f]) + (c \times I_{65}) + (d \times I_{70}) + (e \times I_{\geq 3GPL}) + (f \times I_{\text{at-grade}}) + (g \times P_{ob}) \\ +(h \times P_{ib}) + (i \times I_{R24}) + (j \times I_{\text{flush}}) + (k \times I_{\text{flush}} \times W_{\text{buffer}}) + (l \times P_c) + (m \times P_{hvh}) \\ +(p \times X_{e,ext}) + (q \times \ln[AADT_{en}]) + (r \times \ln[AADT_{e,ext}])$$

The coefficients in this equation (i.e., a, b, c, …, r) are obtained from Table 30 for each severity level j. The site has a speed limit of 60 miles per hour, only 2 GPL through lanes, continuous HO lane access, no outside (roadside) barrier, no buffer, and no horizontal curvature; therefore, I_{65}, I_{70}, $I_{\geq 3GPL}$, $I_{\text{at-grade}}$, P_{ob}, I_{flush}, and P_c are equal to 0.0. $V_{en,j}$ is computed for fatal and incapacitating injury crashes as follows:

$$V_{en,K+A} = 5.207 + (-0.728 \times \ln[54{,}800]) + (0.0) + (0.0) + (0.0) + (0.0) + (0.0) \\ +(-0.0989 \times 1.000) + (0.185 \times 1.0) + (0.0) + (0.0) + (0.0) + (-0.199 \times 0.40) \\ +(-0.0598 \times 0.65) + (-0.0762 \times \ln[5200]) + (-0.0789 \times \ln[5400])$$

$$V_{en,K+A} = -4.099$$

Calculations using the coefficients for incapacitating injury crashes and non-incapacitating injury crashes from Table 30 yield the following results:

$$V_{en,B} = -2.542$$

$$V_{en,C} = -0.876$$

Using these computed values, and the calibration factor $C_{sdf,en}$ of 1.05, the proportion of a fatal crashes is computed using Equation 50 as follows:

$$P_{en,ac,at,K} = \frac{\exp(V_{en,K+A})}{\frac{1.0}{C_{sdf,en}} + \exp(V_{en,K+A}) + \exp(V_{en,B}) + \exp(V_{en,C})} \times P_{K|K+A,en,ac,at}$$

$$= \frac{\exp(-4.099)}{\frac{1.0}{1.05} + \exp(-4.099) + \exp(-2.542) + \exp(-0.876)} \times 0.209$$

$$= 0.0024$$

Similar calculations using Equation 51 to Equation 53 yield the following results:

$$P_{en,ac,at,A} = 0.0090$$

$$P_{en,ac,at,B} = 0.0538$$

$$P_{en,ac,at,C} = 0.2844$$

The proportion of property-damage-only crashes is computed using Equation 54 as follows:

$$P_{en,ac,at,PDO} = 1.0 - (P_{en,ac,at,K} + P_{en,ac,at,A} + P_{en,ac,at,B} + P_{en,ac,at,C})$$

$$= 1.0 - (0.0024 + 0.0090 + 0.0538 + 0.2844)$$

$$= 0.6505$$

The proportion of fatal crashes is multiplied by the total crash frequency obtained in Step 11 using Equation 49 as follows:

$$N_{p,en,ac,at,K} = N_{p,en,ac,at,as} \times P_{en,ac,at,K}$$

$$= 2.124 \times 0.0024$$

$$= 0.005 \text{ crashes/yr}$$

Similar calculations using Equation 49 and the proportions of the other crash severities yield the following results:

$$N_{p,en,ac,at,A} = 0.019 \text{ crashes/yr}$$

$$N_{p,en,ac,at,B} = 0.114 \text{ crashes/yr}$$

$$N_{p,en,ac,at,C} = 0.604 \text{ crashes/yr}$$

$$N_{p,en,ac,at,PDO} = 1.381 \text{ crashes/yr}$$

Apply the crash type distribution, if desired.

The crash type distributions are applied by multiplying the default crash type distribution proportions in Table 32 by the predicted average crash frequencies obtained in Step 11.

The first step in applying the crash type distribution proportions is to select the desired crash type proportion from Table 32. The distributions of interest are the multiple-vehicle distribution and the single-vehicle distribution for ramp entrance speed-change lanes. For example, the proportion of multiple-vehicle crashes having a rear-end manner of collision is 0.661. The proportion of single-vehicle crashes with a fixed object is 0.775.

The second step is to compute the predicted average crash frequency associated with the crash type of interest. Equation 57 is used for this purpose. It is repeated below.

$$N_{p,en,ac,y(j),as} = N_{p,en,ac,y,as} \times P_{en,ac,y(j),as}$$

The predicted average multiple-vehicle crash frequency $N_{p,en,ac,mv,as}$ was computed in Step 11. It is used compute the predicted average rear-end crash frequency as follows:

$$N_{p,en,ac,\text{rear-end},as} = 1.658 \times 0.661$$
$$= 1.096 \text{ crashes/yr}$$

Using the same equation, the predicted average fixed-object crash frequency is computed as 0.361 crashes per year (= 0.466 × 0.775).

2.13.2 SAMPLE PROBLEM 2

The Site/Facility

An existing section of freeway has two 12-foot through lanes, a 14-foot outside shoulder, a 14-foot inside shoulder, a 38-foot median, and continuous median barrier. The agency is considering adding a continuous-access HOV lane to the cross section. The outside shoulder would be reduced to 10 feet and the inside shoulder would be reduced to 6 feet thereby allowing 12 feet to be used for the HOV lane. The width of the two through lanes is unchanged by this conversion.

The existing freeway section is subdivided into sites. The freeway segment of interest is shown in Figure 16. The same segment with the continuous-access HOV lane added is shown in Figure 17.

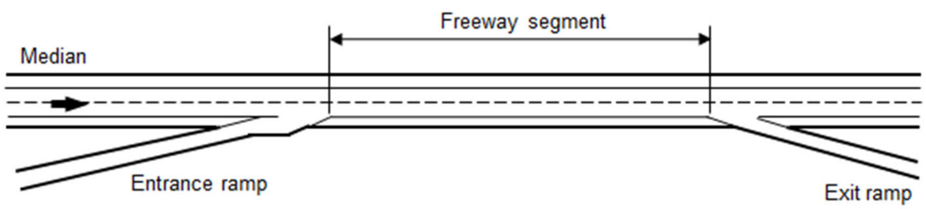


Figure 16. Existing freeway section and segment of interest for sample problem 2.

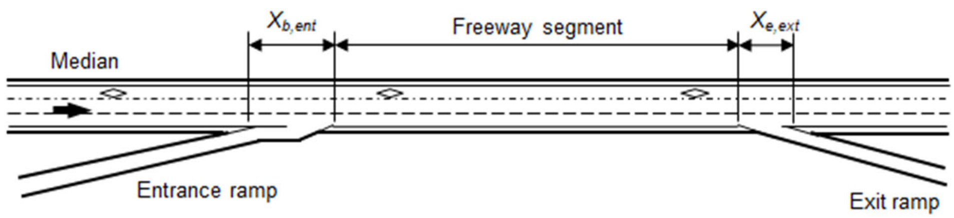


Figure 17. Proposed freeway section and segment of interest for sample problem 2.

The Question

What is the predicted average crash frequency of the existing freeway segment for the specified study year and what is the predicted average crash frequency of the same segment after the HOV lane is added?

The Facts

The study period is one year in duration (i.e., Year 2020). The conditions present during this year are provided in the following list:

Data Common to Both the Existing and Proposed Segment

- 0.58-mi segment length
- 60-mi/h speed limit
- 12-ft lane width
- No horizontal curvature
- Median barrier extends for the length of the site (barrier is centered in median)
- No outside (roadside) barrier
- No rumble strips on outside shoulder
- No rumble strips on inside shoulder
- 30-ft clear zone width
- No weaving section present
- Upstream entrance ramp is 0.14 miles from the segment and has an AADT volume of 5200 vehicles per day (i.e., $X_{b,ent}$ = 0.14 mi; $AADT_{b,ent}$ = 5200 veh/day)

- Downstream exit ramp is 0.07 miles from the segment and has an AADT volume of 5400 vehicles per day (i.e., $X_{e,ext}$ = 0.07 mi; $AADT_{e,ext}$ = 5400 veh/day)
- Freeway AADT is 60,000 vehicles per day in each direction of travel

Data Specific to the Existing Segment

- 2 through lanes
- 14-ft inside shoulder width (paved)
- 14-ft outside shoulder width (paved)
- 38-ft median width
- The proportion of AADT during hours where volume exceeds 1,000 vehicles per hour per lane is 0.90.
- Calibration factors: $C_{fs,ac,mv,fi}$ = 1.07; $C_{fs,ac,sv,fi}$ = 1.07; $C_{fs,ac,mv,pdo}$ = 1.07; $C_{fs,ac,sv,pdo}$ = 1.07; $C_{sdf,fs}$ = 0.92

Data Specific to the Proposed Segment with HOV Lane

- 2 GP through lanes
- 1 HOV lane
- 6-ft inside shoulder width (paved)
- 10-ft outside shoulder width (paved)
- 22-ft median width
- HOV lane is restricted to high-occupancy vehicles 24 hours per day
- Continuous access to and from the HOV lane
- Lane line separation between GP and HOV lanes
- Calibration factors: $C_{fs,ac,at,as}$ = 1.02; $C_{fs,ac,mv,as}$ = 1.02; $C_{sdf,fs}$ = 1.05

Assumptions

- The proportion of hours in the average day where lane volume exceeds 1,000 vehicles per hour per lane is described by the default value obtained from Equation 12. The computed value is 0.42.
- The average speed differential between the inside GP lane and the HO lane is described by the default value obtained from Equation 13. The computed value is 4.1 mi/h.
- The crash type distribution is described by the default values presented in Table 17.

Results

Using the predictive method in Chapter 18 of the HSM Supplement (*2*), the predicted average total crash frequency for the existing freeway segment is determined to be 10.9 crashes per year, and the predicted average fatal-and-injury crash frequency is determined to be 3.0 crashes per year (rounded to one decimal place).

Using the predictive method in this chapter, the predicted average total crash frequency for the proposed freeway segment in this sample problem is determined to be 12.4 crashes per year, and the predicted average fatal-and-injury crash frequency is determined to be 4.7 crashes per year (rounded to one decimal place).

The freeway segment with the HOV lane added is found to increase the average total crash frequency by 14 percent (= 12.4/10.9 × 100 –100). The average fatal-and-injury crash frequency is found to increase by 57 percent. These increases are due to the reduction in shoulder and median widths associated with the conversion as well as the speed differential between the inside GP lane and the HO lane.

The sequence of calculations undertaken to obtain these results are described in the following sections.

Steps – Evaluation of Existing Segment

The predictive models for freeway segments in Chapter 18 are based on the evaluation of two-directional freeway segments. However, the procedure in Section 2.11.2 describes how to use the Chapter 18 method to estimate the predicted average crash frequency of one-directional freeway segments. This procedure is used to evaluate the existing freeway segment described in Figure 16. The steps of the procedure are outlined in the following paragraphs. The application of the Chapter 18 models is not described.

Step 1 – Define project limits and study period.

The project limits for the existing freeway section is established to be the same as for the proposed freeway with the HOV lane. The study period for the existing section is Year 2020, which is the same as for the proposed freeway.

Step 2 – Determine the two-directional AADT.

The two-directional AADT needed for the Chapter 18 freeway segment model equals twice the AADT for the subject one-directional segment. Thus, the two-way AADT is 120,000 vehicles per day (= 2 × 60,000).

Step 3 – Obtain site characteristics.

The site characteristics are provided in the previous section titled "The Facts." The two-directional number of lanes needed for the Chapter 18 SPF equals twice the number of through lanes serving the subject direction of travel. Thus, the Chapter 18 SPF should be for a four-lane facility (= 2 × 2 lanes).

Step 4 – Divide the two-directional freeway into sites.

The existing freeway section is divided into segments and speed-change lanes using the segmentation process described in Chapter 18. The freeway segment of interest is shown in Figure 16. Given that the predictive method described in this chapter has many of the same segmentation criteria as in the Chapter 18 method, the existing freeway segment has the same begin and end points as the proposed freeway segment to which it is being compared.

Step 5 – Compute the one-directional predicted crash frequency.
The predictive method in Chapter 18 is used to evaluate the existing freeway segment as a 4-lane freeway with an AADT volume of 120,000 vehicles per day. The predicted average total crash frequency is determined to be 21.8 crashes per year, and the predicted average fatal-and-injury crash frequency is determined to be 6.0 crashes per year. These crash frequencies include crashes in both travel directions. They are divided by 2 to obtain the predicted average crash frequency for the subject travel direction. The computed values are 10.9 total crashes per year (= 21.8/2) and 3.0 fatal-and-injury crashes per year (= 3.0/2).

Steps – Evaluation of Proposed Segment with HOV Lane

Step 1 through 8
The information obtained for steps 1 through 8 are listed in the previous sections. Observed crash data are not obtained because the EB Method will not be applied.

Step 9—For the selected site, determine and apply the appropriate SPF.
The SPF for freeway segments (i.e., Equation 14) is used to compute the predicted average crash frequency for base conditions. The predicted total crash frequency is computed using the following equation.

$$N_{spf,fs,2,at,as} = L_{s,fs} \times \exp\left(a + b \times \ln\left[AADT_{fs}\right]\right)$$
$$= 0.58 \times \exp(-11.590 + 1.298 \times \ln[60{,}000])$$
$$= 8.551 \text{ crashes/yr}$$

Similarly, the SPF for multiple-vehicle crashes is calculated from Equation 14 to yield the following result:

$$N_{spf,fs,2,mv,as} = 6.211 \text{ crashes/yr}$$

Step 10—Multiply the result obtained in Step 9 by the appropriate AFs.
The AFs in the predictive model equation for freeway segments are described in this step.

Lateral Separation and Access Type ($AF_{1,fs,ac,y,as}$)
The lateral separation is lane line and the access is continuous, which is the base condition for this AF. Hence, the value of $AF_{1,fs,ac,y,as}$ is 1.000 for both total crashes and multiple-vehicle crashes.

Inside Shoulder Width ($AF_{2,fs,ac,y,as}$)
The inside shoulder width AF is computed using Equation 17. This equation is repeated below:

$$AF_{2,fs,ac,y,as} = \exp(a \times [W_{is} - 2])$$

The site has an average inside shoulder width of 6 feet. From Table 9, the coefficient *a* equals −0.0191 for total crashes. The AF value for total crashes is computed as:

$$AF_{2,fs,ac,at,as} = \exp(-0.0191 \times [6 - 2])$$
$$= 0.926$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{2,fs,ac,mv,as}$ = 0.919.

Outside Shoulder Width ($AF_{3,fs,ac,y,as}$)

The subject site has a 10-ft outside shoulder width, which is the base condition for the outside shoulder width AF. Hence, $AF_{3,fs,ac,at,as}$ and $AF_{3,fs,ac,mv,as}$ are equal to 1.000.

Median Width ($AF_{4,fs,ac,y,as}$)

The subject segment has a 22-ft median width, which is the base condition for the median width AF. Hence, $AF_{4,fs,ac,at,as}$ and $AF_{4,fs,ac,mv,as}$ are equal to 1.000.

Median Barrier ($AF_{5,fs,ac,y,as}$)

The median barrier AF is computed using Equation 20. This equation is repeated below:

$$AF_{5,fs,ac,y,as} = (1.0 - P_{ib}) \times 1.0 + P_{ib} \times \exp(a)$$

The subject segment has median barrier that extends for the length of the site so the proportion P_{ib} equals 1.000. From Table 12, the coefficient a equals 0.231 for total crashes. The AF value for total crashes is computed as:

$$AF_{5,fs,ac,at,as} = (1.0 - 1.000) \times 1.0 + 1.000 \times \exp(0.231)$$
$$= 1.260$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{5,fs,ac,mv,as}$ = 1.336.

Outside Barrier ($AF_{6,fs,ac,at,as}$)

The subject site does not have barrier on the outside (roadside), which is the base condition. Hence, $AF_{6,fs,ac,at,as}$ is equal to 1.000. This AF does not apply to multiple-vehicle crashes.

Type C Weaving Section ($AF_{7,fs,ac,y,as}$)

The subject site does not have a one-sided Type C weaving section present, which is the base condition. Hence, $AF_{7,fs,ac,at,as}$ and $AF_{7,fs,ac,mv,as}$ are equal to 1.000.

Average Speed Differential ($AF_{8,fs,ac,y,as}$)

The average speed differential AF is computed using Equation 25. This equation is repeated below:

$$AF_{8,fs,ac,y,as} = \exp(a \times \Delta_v)$$

The subject site has an average speed differential of 4.1 mi/h. From Table 14, the coefficient a equals 0.0178 for total crashes. The AF value for total crashes is computed as:

$$AF_{8,fs,ac,at,as} = \exp(0.0178 \times 4.1)$$
$$= 1.076$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{8,fs,ac,mv,as}$ = 1.099.

High-Volume Hours ($AF_{9,fs,ac,y,as}$)

The high-volume hours AF is computed from Equation 26. This equation is repeated below

$$AF_{9,fs,ac,y,as} = \exp(a \times P_{hvh})$$

The subject site has a proportion of hours with high volume of 0.42. From Table 15, the coefficient *a* equals 0.290 for total crashes. The AF value for total crashes is computed as:

$$\begin{aligned} AF_{9,fs,ac,at,as} &= \exp(0.290 \times 0.42) \\ &= 1.130 \end{aligned}$$

The AF for multiple-vehicle crashes is computed using the same equation but with a different coefficient. This AF is computed as $AF_{9,fs,ac,mv,as} = 1.189$.

Computed Segment Crash Frequency

The AFs are applied to the total crash frequency SPF as follows:

$$\begin{aligned} N^*_{p,fs,2,at,as} &= N_{spf,fs,2,at,as} \times (AF_{1,fs,ac,at,as} \times \ldots \times AF_{9,fs,ac,at,as}) \\ &= 8.551 \times (1.000 \times 0.926 \times 1.000 \times 1.000 \times 1.260 \times 1.000 \times 1.000 \times 1.076 \times 1.130) \\ &= 8.551 \times 1.418 \\ &= 12.126 \text{ crashes/yr} \end{aligned}$$

The AFs are applied to the multiple-vehicle crash frequency SPF as follows:

$$\begin{aligned} N^*_{p,fs,2,mv,as} &= N_{spf,fs,2,mv,as} \times (AF_{1,fs,ac,mv,as} \times \ldots \times AF_{5,fs,ac,mv,as} \times AF_{7,fs,ac,mv,as} \times \ldots \times AF_{9,fs,ac,mv,as}) \\ &= 6.211 \times (1.000 \times 0.919 \times 1.000 \times 1.000 \times 1.336 \times 1.000 \times 1.099 \times 1.189) \\ &= 6.211 \times 1.605 \\ &= 9.971 \text{ crashes/yr} \end{aligned}$$

Step 11—Multiply the result obtained in Step 10 by the appropriate calibration factor.

A calibration factor of 1.02 has been determined for the total crash frequency SPF and a calibration of 1.02 has been determined for multiple-vehicle crash frequency SPF. The predicted average total crash frequency is computed as:

$$\begin{aligned} N_{p,fs,2,at,as} &= N^*_{p,fs,2,at,as} \times C_{fs,ac,at,as} \\ &= 12.126 \times 1.02 \\ &= 12.369 \text{ crashes/yr} \end{aligned}$$

The unadjusted predicted multiple-vehicle crash frequency is computed as:

$$\begin{aligned} N'_{p,fs,2,mv,as} &= N^*_{p,fs,2,mv,as} \times C_{fs,ac,mv,as} \\ &= 9.971 \times 1.02 \\ &= 10.171 \text{ crashes/yr} \end{aligned}$$

Finally, the predicted average multiple-vehicle crash frequency is computed using Equation 3 as follows.

$$N_{p,fs,2,mv,as} = \min\left[N_{p,fs,2,at,as}, N'_{p,fs,2,mv,as}\right]$$
$$= \min[12.369, 10.171]$$
$$= 10.171 \text{ crashes/year}$$

The predicted average single-vehicle crash frequency is calculated using Equation 5 as follows:

$$N_{p,fs,2,sv,as} = N_{p,fs,2,at,as} - N_{p,fs,2,mv,as}$$
$$= 12.369 - 10.171$$
$$= 2.198 \text{ crashes/yr}$$

Step 12—If there is another year to be evaluated in the evaluation period for the selected site, return to Step 8. Otherwise, proceed to Step 13.
The study period is one year (i.e., 2020), so steps 8 through 11 do not need to be repeated for another year.

Step 13—Apply site-specific EB Method (if applicable) and apply crash distributions.
This step consists of three optional sets of calculations—site-specific EB Method, severity distribution, and crash type distribution.

Apply the site-specific EB Method to a future time period, if appropriate.

The site-specific EB Method is not applied in this sample problem.

Apply the severity distribution, if desired.

To apply the SDFs, the systematic component of crash severity likelihood $V_{fs,j}$ is computed for each severity level j using Equation 33 as follows:

$$\begin{aligned} V_{fs,j} = a &+ \left(b \times \ln\left[AADT_{fs}\right]\right) + (c \times I_{65}) + (d \times I_{70}) + (e \times I_{\geq 3GPL}) + \left(f \times I_{\text{at-grade}}\right) + (g \times P_{ob}) \\ &+ (h \times P_{ib}) + (i \times I_{R24}) + (j \times I_{\text{flush}}) + (k \times I_{\text{flush}} \times W_{\text{buffer}}) + (l \times P_c) + (m \times P_{hvh}) \\ &+ \left(n \times X_{b,ent}\right) + \left(p \times X_{e,ext}\right) + \left(q \times \ln\left[AADT_{b,ent}\right]\right) + \left(r \times \ln\left[AADT_{e,ext}\right]\right) \end{aligned}$$

The coefficients in this equation (i.e., a, b, c, …, r) are obtained from

Table 16 for each severity level *j*. The site has a speed limit of 60 miles per hour, only 2 GPL through lanes, continuous HO lane access, no outside (roadside) barrier, no buffer, and no horizontal curvature; therefore, I_{65}, I_{70}, $I_{\geq 3GPL}$, $I_{\text{at-grade}}$, P_{ob}, I_{flush}, and P_c are equal to 0.0. $V_{fs,j}$ is computed for fatal and incapacitating injury crashes as follows:

$$V_{fs,K+A} = 5.207 + (-0.703 \times \ln[60{,}000]) + (0.0) + (0.0) + (0.0) + (0.0) + (0.0) + (-0.0989 \times 1.000) + (0.185 \times 1.0) + (0.0) + (0.0) + (0.0) + (-0.199 \times 0.42) + (-0.0372 \times 0.14) + (-0.0598 \times 0.07) + (-0.0762 \times \ln[5200]) + (-0.0789 \times \ln[5400])$$

$$V_{fs,K+A} = -3.864$$

Calculations using the coefficients for incapacitating injury crashes and non-incapacitating injury crashes from

Table 16 yield the following results:

$$V_B = -2.137$$

$$V_C = -0.814$$

Using these computed values, and the calibration factor $C_{sdf,fs}$ of 1.05, the proportion of a fatal crashes is computed using Equation 28 as follows:

$$P_{fs,ac,at,K} = \frac{\exp(V_{fs,K+A})}{\frac{1.0}{C_{sdf,fs}} + \exp(V_{fs,K+A}) + \exp(V_{fs,B}) + \exp(V_{fs,C})} \times P_{K|K+A,fs,ac,at}$$

$$= \frac{\exp(-3.864)}{\frac{1.0}{1.05} + \exp(-3.864) + \exp(-2.137) + \exp(-0.814)} \times 0.209$$

$$= 0.0029$$

Similar calculations using Equation 29 to Equation 31 yield the following results:

$$P_{fs,ac,at,A} = 0.0108$$

$$P_{fs,ac,at,B} = 0.0769$$

$$P_{fs,ac,at,C} = 0.2888$$

The proportion of property-damage-only crashes is computed using Equation 32 as follows:

$$P_{fs,ac,at,PDO} = 1.0 - (P_{fs,ac,at,K} + P_{fs,ac,at,A} + P_{fs,ac,at,B} + P_{fs,ac,at,C})$$

$$= 1.0 - (0.0029 + 0.0108 + 0.0769 + 0.2888)$$

$$= 0.6206$$

The proportion of fatal crashes is multiplied by the total crash frequency obtained in Step 11 using Equation 27 as follows:

$$N_{p,fs,2,at,K} = N_{p,fs,2,at,as} \times P_{fs,ac,at,K}$$

$$= 12.369 \times 0.0029$$

$$= 0.035 \text{ crashes/yr}$$

Similar calculations using Equation 27 and the proportions of the other crash severities yield the following results:

$$N_{p,fs,2,at,A} = 0.134 \text{ crashes/yr}$$

$$N_{p,fs,2,at,B} = 0.951 \text{ crashes/yr}$$

$$N_{p,fs,2,at,C} = 3.573 \text{ crashes/yr}$$

$$N_{p,fs,2,at,PDO} = 7.676 \text{ crashes/yr}$$

Apply the crash type distribution, if desired.

The crash type distributions are applied by multiplying the default crash type distribution proportions in Table 17 by the predicted average crash frequencies obtained in Step 11.

The first step in applying the crash type distribution proportions is to select the desired crash type proportion from Table 17. For example, the proportion of multiple-vehicle crashes having a rear-end manner of collision is 0.686. The proportion of single-vehicle crashes with a fixed object is 0.780.

The second step is to compute the predicted average crash frequency associated with the crash type of interest. Equation 34 is used for this purpose. It is repeated below.

$$N_{p,fs,n,y(j),as} = N_{p,fs,n,y,as} \times P_{fs,ac,y(j),as}$$

The predicted average multiple-vehicle crash frequency $N_{p,fs,2,mv,as}$ was computed in Step 11. It is used compute the predicted average rear-end crash frequency as follows:

$$N_{p,fs,2,\text{rear-end},as} = 10.171 \times 0.686$$
$$= 6.977 \text{ crashes/yr}$$

Using the same equation, the predicted average fixed-object crash frequency is computed as 1.715 crashes per year (= 2.198 × 0.780).

Chapter 3. Overview of Implementation Tool

The NCHRP 17-89A project team developed a spreadsheet-based implementation tool for the predictive method presented in Chapter 2. This chapter initially provides an overview of the implementation tool. It then describes how to apply the tool in predictive analysis. Finally, it describes how to interpret the results.

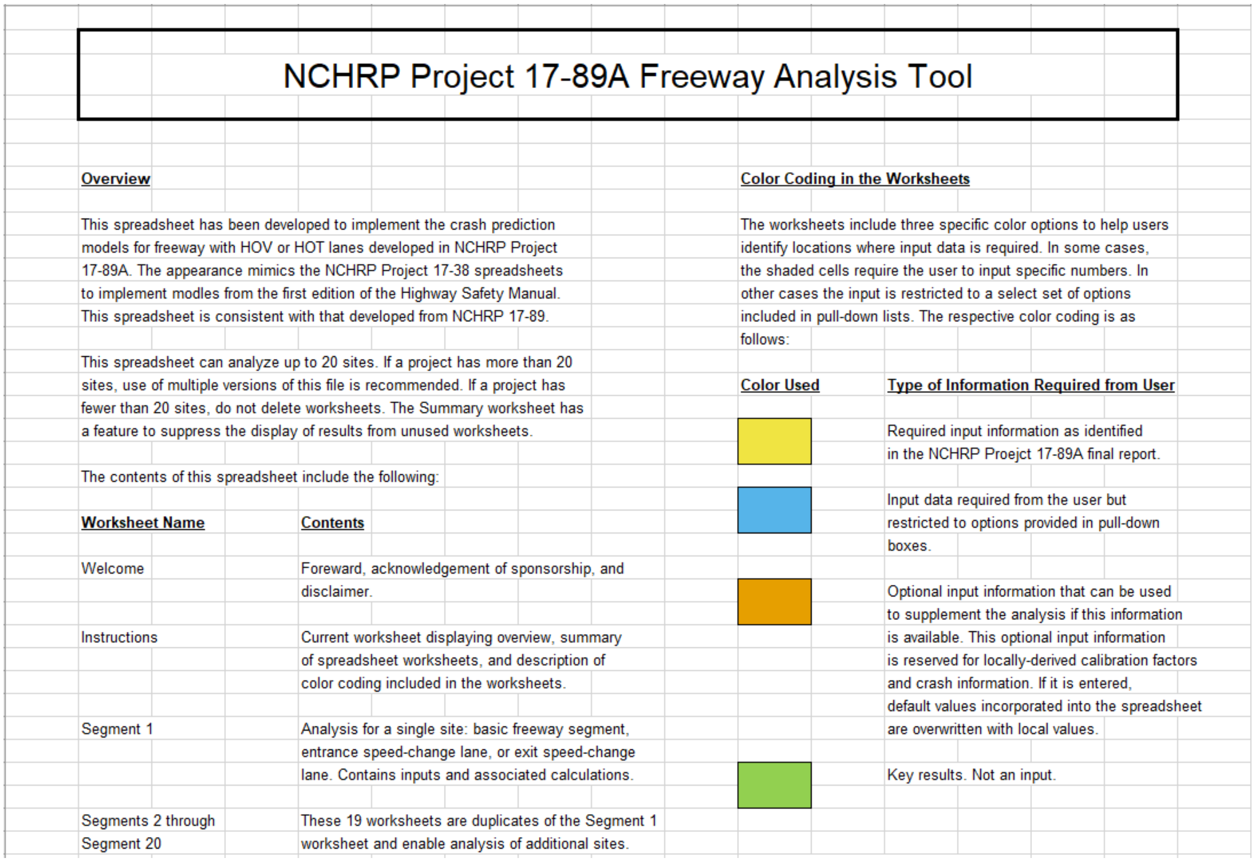
The spreadsheet tool provides the following predicted values: single-vehicle (SV) and multiple-vehicle (MV) crash frequencies, fatal-and-injury (FI) and property-damage-only (PDO) crash frequencies, the distribution of FI crashes by severity level, and the distribution of crash types for SV and MV crashes. The implementation tool provides a direct application of the predictive method and does not include any additions or extensions.

3.1 GETTING STARTED

The implementation tool contains 25 worksheets, including the following:

- **Welcome**. This worksheet includes a foreword, acknowledgements, and disclaimer.
- **Instructions**. This worksheet includes an overview of the tool and the worksheets contained within. Additionally, this worksheet includes a review of the color coding in the worksheets (and associated type of information required from the user), cell protection in the worksheet, and input guidance.
- **Segment 1** through **Segment 20**. Each of these worksheets contains input data for crash frequency and severity models for basic freeway segments, entrance speed-change lanes, and exit speed-change lanes. Each sheet additionally provides detailed calculations and results by crash type and severity from the predictive method.
- **LocalValues**. This worksheet provides the user the capability to provide calibration factors and override default SDFs and crash type distributions.
- **Summary**. This worksheet provides a summary of the crash predictions from each segment worksheet, allows inputs for historic crash data, and computes expected crash frequency using the EB method.
- **Menus**. This worksheet defines the pull-down options used on the other worksheets.

Figure 18 provides a screenshot of part of the Instructions worksheet. This worksheet provides an overview of the contents of the implementation tool. To navigate among worksheets, the user may select any worksheet tab at the bottom of the workbook window. For an analyst's first safety evaluation using this tool, the analyst should select and review the Welcome and Instructions worksheets.



NCHRP Project 17-89A Freeway Analysis Tool

Overview

This spreadsheet has been developed to implement the crash prediction models for freeway with HOV or HOT lanes developed in NCHRP Project 17-89A. The appearance mimics the NCHRP Project 17-38 spreadsheets to implement modles from the first edition of the Highway Safety Manual. This spreadsheet is consistent with that developed from NCHRP 17-89.

This spreadsheet can analyze up to 20 sites. If a project has more than 20 sites, use of multiple versions of this file is recommended. If a project has fewer than 20 sites, do not delete worksheets. The Summary worksheet has a feature to suppress the display of results from unused worksheets.

The contents of this spreadsheet include the following:

Worksheet Name	Contents
Welcome	Foreward, acknowledgement of sponsorship, and disclaimer.
Instructions	Current worksheet displaying overview, summary of spreadsheet worksheets, and description of color coding included in the worksheets.
Segment 1	Analysis for a single site: basic freeway segment, entrance speed-change lane, or exit speed-change lane. Contains inputs and associated calculations.
Segments 2 through Segment 20	These 19 worksheets are duplicates of the Segment 1 worksheet and enable analysis of additional sites.

Color Coding in the Worksheets

The worksheets include three specific color options to help users identify locations where input data is required. In some cases, the shaded cells require the user to input specific numbers. In other cases the input is restricted to a select set of options included in pull-down lists. The respective color coding is as follows:

Color Used	Type of Information Required from User
(yellow)	Required input information as identified in the NCHRP Proejct 17-89A final report.
(blue)	Input data required from the user but restricted to options provided in pull-down boxes.
(orange)	Optional input information that can be used to supplement the analysis if this information is available. This optional input information is reserved for locally-derived calibration factors and crash information. If it is entered, default values incorporated into the spreadsheet are overwritten with local values.
(green)	Key results. Not an input.

Figure 18. Instructions worksheet screenshot.

The Instructions worksheet provides an overview of the type of information required from the user by color coding. Yellow cells in the spreadsheet tool require the analyst to directly input values. Blue cells indicate the analyst may select the required data input from a dropdown selection menu. Orange cells indicate the data input is not required and the analyst may enter the data to supplement the analysis. Finally, green cells indicate key results of the predictive method and are not data input cells. Cells in the spreadsheet not used for data entry are locked to prevent inadvertent changes. The Instructions worksheet provides the password to unlock worksheets.

3.2 ANALYSIS STEPS

This section outlines the steps in conducting a safety evaluation using the spreadsheet tool. These steps are consistent with other facility type evaluations using an HSM Part C predictive method. These steps should be taken for each safety evaluation using the predictive method. This guide assumes the predictive models and crash type (and severity) distributions have been calibrated for application to sites in the local jurisdiction.

Step 1 – Define Project Limits

The analyst defines the physical extent of the freeway section for evaluation and typically includes two or more sites that are physically connected to form a functioning freeway. The selection of the project limits will depend on the purpose of the study, which may be limited to one specific site, a group of contiguous sites, or an entire facility (and its associated sites). If comparing design alternatives, the project limits should be the same for all alternatives (and should generally be based on the combined extents of alternatives to encompass all potential impacts).

Step 2 – Define Study Period

For this implementation tool, the spreadsheet predicts the average crash frequency for a one-year time period based upon a single set of AADT values and a single set of geometric design and traffic control features. If the analyst desires to predict crashes for multiple years with different AADT values for each year and/or different geometric design and traffic control features for each year, then the average crash frequency should be computed for each year using separate Segment worksheets or separate versions of the spreadsheet. The results may be manually aggregated.

This implementation tool cannot be used to apply the EB method when (a) the study period is defined to be different from the consecutive years for which observed crash data are available (i.e., the crash period) and (b) one or more of the input values (i.e., traffic volume, geometric design, or traffic control feature) changes between the study period and the crash period. The tool does not implement that portion of the EB method that is used to address this situation. The question of whether the EB method is applicable is determined in a later step (see Step 4).

Step 3 – Acquire Traffic Volume Data

During this step, the analyst collects required AADT data. AADT data are required for all freeway segments, entrance ramps, and exit ramps in the project limits. For a past period, the AADT may be determined using data recorders or estimated from a sample survey. For a future period, the AADT may be a forecast estimate based on appropriate land use planning and traffic volume forecasting models. Some agencies maintain AADT estimates for a freeway mainline facility based on the direction of traffic or for both directions combined. For this predictive method, the AADT value should be specifically for the analysis direction. If the analyst only has bi-directional AADT for a given freeway segment, then the analyst may divide the AADT by two to estimate the directional AADT for that segment. Further, the directional AADT includes mainline freeway traffic in both the GP and the HO lanes.

Step 4 – Acquire Observed Crash Data

When the analyst is working with an existing facility (or alternatives for an existing facility), the EB method may be applied to obtain a more reliable estimate of the expected average crash frequency. If the EB method will be applied, then the analyst collects observed crash data during this step. Appendix B of the 2014 supplement to the HSM (*2*) provides guidance on when the EB method is and is not applicable.

When determining whether the EB method is applicable, a decision is made whether to apply the site-specific EB method or the project-level EB method. The analyst may factor into this decision the fact that the implementation tool cannot be used to apply the project-level EB method. If desired, the project-level EB method may be manually applied outside of the implementation tool.

Step 5 – Divide Project into Individual Sites

Using the segmentation criteria described in Chapter 2 of this document, the analyst may divide the project into individual sites including basic freeway segments, entrance speed-change lanes, or exit speed-change lanes.

Step 6 – Acquire Geometric Design, Operational, and Traffic Control Data

In this step, the analyst collects the data needed to apply the predictive method including any geometric design, operational, and traffic control data. For this predictive method, these data elements are those that have been found to have a significant relationship with crash frequency and/or crash severity. The analyst will need to collect these data for each site within the project limits. For operational data elements (including speed differential between the leftmost GP lane and the HO lane and the proportion of high-volume hours), data may be obtained from permanent count stations, estimated from other data sources, or marked as unavailable. If operational data are not available, then the tool includes the option to use a default value.

Step 7 – Assign Observed Crashes

If the analyst selected to use the EB method in Step 4, then the crash data acquired in that step are assigned to the individual sites on the Summary worksheet and the site-specific EB method is applied. As discussed in Step 2, the implementation tool cannot be used to apply the EB method if the study period is different from the crash period and one or more inputs have changed between these two periods. If the implementation tool cannot be used to apply the EB method, then the EB method may be manually applied outside the spreadsheet. If crashes cannot be assigned to individual sites and are only known to have occurred within the project as a whole, the project-level EB method may be manually applied outside of the spreadsheet. The HSM and HSM Supplement describe the steps of the site-specific EB method and the project-level EB method (*2,4*).

Step 8 – Obtain and Review Results

Once the analyst has entered data into the spreadsheet tool, the results are automatically compiled in the Summary worksheet. All calculations are done with cell formulas, and there are no Microsoft (MS) Excel macros. The individual Segment worksheets display FI and PDO predicted crash frequency, as well as the distribution of crash severities and crash types. The Summary worksheet displays FI and PDO predicted crash frequency for each site being analyzed as well as FI and PDO expected crash frequency if applicable. Cells containing key results are highlighted in green.

3.3 SEGMENT WORKSHEET SITE DATA ENTRY

This section provides guidance on entering data into the main Segment worksheets (of which there are 20 worksheets). The analyst only needs to use the number of worksheets for which there are segments being analyzed; however, if more than 20 worksheets are needed, then the analyst will need to use multiple workbooks to complete the analysis. The results in the Summary worksheet can be aggregated separately.

Figure 19 provides a sample partial screenshot of Segment input data. Under the General Information section, the analyst may input their name, their agency or company, and date the analysis was performed (the worksheet defaults to the current date). The worksheet also allows the analyst to enter location information for the study segment and analysis year.

For the segment data, there are several items for which the analyst should be aware, including the following:

General Information and Input Data			
General Information		**Location Information**	
Analyst	SCH	Freeway	
Agency or Company	VHB	Direction	
Date Performed	5/24/2021	Location Description	
		Jurisdiction	
		Analysis Year	2021

Input Data	Base Condition	Site Conditions	Input Checks
Site type (Basic Segment, Ramp Entrance Speed-Change Lane, Ramp Exit Speed-Change Lane):	--	Basic Freeway Segment (FS)	-
Segment Length (L_s), mi:	--	1	-
Directional freeway AADT ($AADT_{fs}$), veh/day: $AADT_{MAX}$ = 121,000 (veh/day)	--	65,000	OK
$AADT_{MIN}$ = 0 (veh/day)	--		OK
Entrance ramp AADT ($AADT_{en}$), veh/day: $AADT_{MAX}$ = 79,000 (veh/day)	--		N/A
Exit ramp AADT ($AADT_{ex}$), veh/day: $AADT_{MAX}$ = 91,000 (veh/day)	--		N/A
Number of general purpose lanes, n_{gp}:	--	2	-
Number of HOV/HOT lanes, n_{HO}:	--	1	N/A
Cross Section Data			
Lateral separation type:	Continuous Access	Continuous Access	-
HOV/HOT buffer separation width (W_B), ft:	0		N/A
Distance to downstream exit from closest access (X), (mi)	0		N/A
Inside shoulder width (W_{IS}), ft:	2	2	OK
Outside shoulder width (W_{OS}), ft:	10	10	OK
Median width (W_M), ft:	22	22	OK
Segment length with inside median barrier (L_{IB}), mi:	0	0.1	OK
Segment length with outside barrier (L_{OB}), mi:	0	0	OK
Ramp Access Data			
Presence of type of Type C weaving section (I_C):	Not Present	No	-
Operational Data			
Is the percent of hours that are high volume hours available?	-	No - Use Default Value	-
Proportion of high volume hours (P_{HV}):	-	0	N/A
Is the average speed differential between HOV/HOT lane and leftmost GPL available?	-	No - Use Default Value	-
Average speed differential (X), mph:	0	3	N/A
Additional Severity Distribution Function Data			
Posted speed limit (X), mph:	-	65 MPH	-
Distance from begin milepost to upstream entrance ramp gore ($X_{b,ent}$), mi:		0.25	OK

Figure 19. Screenshot of Segment worksheet.

- Cell color: As noted in the Instructions worksheet, cell color has an important meaning for input data requirements and types. However, the analyst should be further aware of two colors:
    - Grayed-out rows. Based on prior inputs, some cells will be grayed-out because they are not applicable for the given circumstances. For example, when the segment is a basic freeway segment, the entrance ramp AADT and exit ramp AADT are not applicable. If the analyst does not have operational data available, the input row will be grayed-out since the default will be selected instead. Analysts should note that while the row is grayed-out, data can be entered but will not be used by the spreadsheet. If the analyst changes an input value leading to the row no longer being grayed-out, the data element will be used by the tool.
    - Red cells. If data exceed the bounds of the predictive method or fails an input check, the data entry cell will turn red. Additionally, the input check will provide an indication of the issue. This is intended as a warning to the analyst, but the spreadsheet will still complete the calculation.
- Base condition: When applicable, this cell provides the assumed base condition for the predictive method consistent with Chapter 2.
- Input checks: For most data elements, the spreadsheet tool employs simple logic (not macro-based) to compare entered site conditions against a minimum or maximum value (when applicable) or against other values as appropriate. For example, if the length of

segment with inside median barrier is longer than the total segment length, the spreadsheet will assume a maximum proportion of segment with inside median barrier of 1.0 but will alert the analyst that the segment length with inside median barrier is too large. If the input check does not find any errors, it will return "OK". If there is no applicable value the analyst may enter, the input check will return "N/A".

- Notes: To support the analyst when entering data, the spreadsheet provides data entry notes. The cells with red markers in the upper right-hand corner include notes with supporting information.
- Default values: For operational data elements, it is possible the analyst will not have access to supporting data. The analyst may select yes to enter operational data if available, or may choose to use a default value if the answer is no. The spreadsheet calculates the default value for operational measures using freeway mainline AADT with the equations provided in Chapter 2.

Figure 20 provides a screenshot of supporting calculations included on the Segment worksheet. This worksheet for each segment provides the calculation of total crash frequency and multiple-vehicle crash frequency from the base SPFs for basic freeway segments, entrance speed-change lanes, and exit speed-change lanes. The worksheet then provides the calculations for each AF for applicable site types and crash types. As shown, the worksheet then provides predicted crash frequency, including the calibration factor and AFs, for the selected segment type.

Type C Weaving Section

Applicability	a	X	AF_{WC}
FS TOT	0.224	0	1.000
FS MV	0.254	0	1.000

High Volume Duration

Applicability	a	User	Default	Value	AF_{HV}
FS TOT	0.290	0	0.446	0.000	1.000
FS MV	0.412	0	0.446	0.000	1.000

Average Speed Difference

Applicability	a	User	Default	Value	AF_{V}
FS TOT	0.0178	3	4.191	4.190	1.077
FS MV	0.023	3	4.191	4.190	1.101
EN SCL TOT	0.0232	3	4.191	4.190	1.102
EN SCL MV	0.0261	3	4.191	4.190	1.116
EX SCL TOT	0.0232	3	4.191	4.190	1.102
EX SCL MV	0.0261	3	4.191	4.190	1.116

HOV/HOT Lanes

Applicability	a	n_{HO}	AF_{HO}
EN SCL TOT	0.293	0	1.000
EN SCL MV	0.261	0	1.000
EX SCL TOT	0.293	0	1.000
EX SCL MV	0.261	0	1.000

Crash Prediction Model

SPF	C	N_{spf}	$AF_{LS,DA}$	AF_{IS}	AF_{OS}	AF_{MW}	AF_{IB}	AF_{OB}	AF_{WC}	AF_{HV}	AF_{V}	AF_{HO}	N_{P}
FS TOT	1.00	1.636	1.000	1.000	1.000	1.000	1.260	1.000	1.000	1.000	1.077	-	2.220
FS MV	1.00	1.205	1.000	1.000	1.000	1.000	1.336	-	1.000	1.000	1.101	-	1.773
EN SCL TOT	1.00	0.000	1.000	1.000	1.000	1.000	1.260	1.000	-	-	1.102	1.000	Type Not Selected
EN SCL MV	1.00	0.000	1.000	1.000	1.000	1.000	1.336	-	-	-	1.116	1.000	Type Not Selected
EX SCL TOT	1.00	0.000	1.000	1.000	1.000	1.000	1.260	1.000	-	-	1.102	1.000	Type Not Selected
EX SCL MV	1.00	0.000	1.000	1.000	1.000	1.000	1.336	-	-	-	1.116	1.000	Type Not Selected

Figure 20. Segment worksheet AF calculations screenshot.

The worksheet next provides the SDF factors for each input and provides the severity distribution for the selected segment type. Finally, the spreadsheet incorporates crash type distributions to provide predicted crash frequency by crash type and severity for the selected segment type. Figure 21 provides an example screenshot of the predicted crash frequency by crash type and severity for an example freeway segment. Note that the values are 0.00 for unselected segment types.

Predicted Crash Frequency by Crash Type and Severity - Freeway Segments

Severity	P		Multiple Vehicle Crash Type					Single Vehicle Crash Type					Total
			Head-On	Right Angle	Rear-End	Sideswipe	Other	Animal	Fixed Obj.	Other Obj.	Parked Veh.	Other	
K	0.006		0.000	0.000	0.007	0.002	0.001	0.000	0.002	0.000	0.000	0.000	0.014
A	0.023		0.000	0.002	0.028	0.009	0.002	0.000	0.008	0.001	0.000	0.001	0.052
B	0.118		0.001	0.008	0.144	0.046	0.011	0.000	0.041	0.006	0.000	0.005	0.262
C	0.255		0.002	0.018	0.310	0.099	0.024	0.001	0.089	0.013	0.000	0.011	0.566
PDO	0.597		0.005	0.041	0.727	0.231	0.055	0.002	0.208	0.032	0.000	0.026	1.326
Total			0.009	0.069	1.217	0.387	0.092	0.003	0.349	0.053	0.000	0.043	2.220

Predicted Crash Frequency by Crash Type and Severity - Entrance Speed-Change Lanes

Severity	P		Multiple Vehicle Crash Type					Single Vehicle Crash Type					Total
			Head-On	Right Angle	Rear-End	Sideswipe	Other	Animal	Fixed Obj.	Other Obj.	Parked Veh.	Other	
K	0.006		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
A	0.023		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
B	0.115		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
C	0.248		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
PDO	0.609		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
Total			0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Predicted Crash Frequency by Crash Type and Severity - Exit Speed-Change Lanes

Severity	P		Multiple Vehicle Crash Type					Single Vehicle Crash Type					Total
			Head-On	Right Angle	Rear-End	Sideswipe	Other	Animal	Fixed Obj.	Other Obj.	Parked Veh.	Other	
K	0.006		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
A	0.023		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
B	0.115		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
C	0.248		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
PDO	0.609		-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
Total			0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Figure 21. Segments worksheet predicted crash frequency by crash type and severity.

3.4 LOCALVALUES WORKSHEET DATA ENTRY

The predictive models for freeway facilities with HOV/HOT lanes, including SDFs and crash type distributions, were developed using data from specific jurisdictions and time periods. Calibration to current local conditions account for differences between the model development conditions and the local conditions being evaluated. Further, calibration to local conditions supports comparison for alternatives considering a different facility type using calibrated models. The LocalValues worksheet contains input fields (orange cells) allowing the analyst to include locally derived calibration factors, severity distributions or functions, and crash type distributions. The data entered in this sheet are applied to all 20 of the segment worksheets. If the analyst leaves the orange cells blank, then the spreadsheet will apply the default values.

Figure 22 provides a sample application of local calibration factors entered into the LocalValues worksheet. If available, local calibration values are preferred for use in the predictive models.

Local Calibration Factors

Crash Prediction Model	Default	Local Calibration Facto	Use
Basic Freeway Segment (FS), Total	1.00	1.05	1.05
Basic Freeway Segment (FS), Multiple Vehicle	1.00	1.10	1.10
Entrance Speed-Change Lane (EN), Total	1.00		1.00
Entrance Speed-Change Lane (EN), Multiple Vehicle	1.00		1.00
[illegible]	[illegible]		[illegible]

Figure 22. Local calibration factors in LocalValues worksheet.

The predictive method for freeway facilities with HOV/HOT lanes includes SDFs based on several geometric, operational, and traffic control characteristics. The predictive method predicts the proportion for each crash severity based on these characteristics. Figure 24 provides the analyst the opportunity for the analyst to override the severity distribution based on proportions using local data. The proportions may be directly entered in the orange cells labelled local proportion for each segment type. Alternatively, the analyst may enter local calibration factors fatal and injury crashes for use in tandem with the SDF. For each segment, the spreadsheet prioritizes the local proportion (if provided), followed by the calibration factor (which is assumed to be 1.00 unless the analyst enters a different value). Ultimately, the SDF provides the proportion of K, A, B, C, and O crashes according to the KABCO scale. Similarly, the spreadsheet provides default values for crash types. Figure 23 shows that local crash type proportions may be entered. The sum of proportions should be 1.0 for each segment type for each MV crashes and SV crashes.

Severity Distribution Functions			
Freeway Segments - Probability of severity K, A, B, C, and O	Local Proportion	Local Calibration Factor	Use
$P_{fr,K}$		1.05	1.05
$P_{fr,A}$			
$P_{fr,B}$			
$P_{fr,C}$			
$P_{fr,O}$		N/A	
trance Speed-Change Lanes - Probability of severity K, A, B, C, and	Local Proportion	Calibration Factor	
$P_{en,K}$			1.00
$P_{en,A}$			
$P_{en,B}$			
$P_{en,C}$			
$P_{en,O}$		N/A	
Exit Speed-Change Lanes - Probability of severity K, A, B, C, and O	Local Proportion	Calibration Factor	
$P_{ex,K}$			1.00
$P_{ex,A}$			
$P_{ex,B}$			
$P_{ex,C}$			
$P_{ex,O}$		N/A	

Figure 24. Severity distribution function local proportions or calibration factors.

Crash Type Distributions - Local Value										
	Mutiple Vehicle Crash Type					Single Vehicle Crash Type				
Site Type	Head-On	Right Angle	Rear-End	Sideswipe Same Dir.	Other	Animal	Fixed Object	Other Object	Parked Vehicle	Other
Freeway Segment										
Entrance Speed Change Lane										
Exit Speed Change Lane										

Figure 23. Crash type distribution local values.

3.4 SUMMARY WORKSHEET OVERVIEW

Figure 25 provides an example screenshot of the summary worksheet. This worksheet aggregates the predicted average crash frequency for all segments in which analysts enter data. The segment type and description for each segment also translates to the summary worksheet. The analyst may choose to select yes for the option to conduct a site-based EB analysis and enter the number of years of crash data. The spreadsheet automatically calculates the overdispersion parameter and weighted adjustment. The analyst enters the crash data (all years combined for each site) in the orange cells for each row (separately for FI and PDO crashes). From this, the spreadsheet determines expected FI crashes and expected PDO crashes. The spreadsheet calculates project totals as shown in green cells.

Summary and EB Analysis

Perform Empirical Bayes (EB) analysis? Yes

Years of crash data used? 3

Summary of Sites and Predicted Crashes						Observed and Expected Crashes							
				Predicted Average Crash Frequency		Overdispersion Parameter, k		Observed Crashes, All Years		Weighted Adjustment, w		Expected Average Crash Frequency	
Segment	Type	Description	Analyze?	FI	PDO	FI	PDO	FI	PDO	FI	PDO	FI	PDO
1	Basic Freeway Segment (FS)	MM 1.20 to MM 1.30	Yes	0.939	1.393	0.366	0.366	4	6	0.493	0.395	1.139	1.760
2	Entrance Speed-Change Lane (EN	MM 1.30 to MM 1.42	Yes	0.475	0.990	0.322	0.322	2	3	0.686	0.511	0.535	0.995
3	0	0		-	-	0.072	0.072			-	-	-	-
4	0	0		-	-	0.072	0.072			-	-	-	-
5	0	0		-	-	0.072	0.072			-	-	-	-
6	0	0		-	-	0.072	0.072			-	-	-	-
7	0	0		-	-	0.072	0.072			-	-	-	-
8	0	0		-	-	0.072	0.072			-	-	-	-
9	0	0		-	-	0.072	0.072			-	-	-	-
10	0	0		-	-	0.072	0.072			-	-	-	-
11	0	0		-	-	0.072	0.072			-	-	-	-
12	0	0		-	-	0.072	0.072			-	-	-	-
13	0	0		-	-	0.072	0.072			-	-	-	-
14	0	0		-	-	0.072	0.072			-	-	-	-
15	0	0		-	-	0.072	0.072			-	-	-	-
16	0	0		-	-	0.072	0.072			-	-	-	-
17	0	0		-	-	0.072	0.072			-	-	-	-
18	0	0		-	-	0.072	0.072			-	-	-	-
19	0	0		-	-	0.072	0.072			-	-	-	-
20	0	0		-	-	0.072	0.072			-	-	-	-
			Project Totals:	1.414	2.382			6	9			1.674	2.754

Figure 25. Summary Worksheet Screenshot.

Chapter 4. Using Results

4.1 PERFORMANCE MEASURES

Transportation projects are often assessed through a variety of quantitative and qualitative performance measures. To support data-driven safety analysis, transportation safety is assessed through measures of crash frequency and crash severity. Crash frequency is typically measured as the number of crashes per year, for all crashes or for target crash types. Crash severity is measured by level of injury (typically using K, A, B, C, and O on the KABCO scale). However, for measuring performance of existing and planned freeway facilities with HO lanes, other factors, including the following, are often assessed:

- Operational performance.
- Cost.
- Right-of-way needs and environmental impacts.
- Timeframe for implementation.

Transportation projects are evaluated as alternatives to a no-build scenario. However, for freeway facilities with HO lanes, the alternatives may consider building a new facility, widening an existing facility, or re-allocating existing pavement width. The HOV/HOT Informational Guide provides additional discussion of performance measures (*6*).

4.2 CRASH FREQUENCY AND SEVERITY

The predictive method presented in Chapter 2 provides a crash prediction models for total crash frequency and for multiple-vehicle crash frequency. While this method does not include separate models for predicting single-vehicle crashes or fatal and injury crashes, these performance measures may be directly calculated using the crash prediction models and SDFs provided in the method. Their calculation proceeds as follows:

- Total crash frequency: Calculated directly from crash prediction models.
- Multiple-vehicle crash frequency: Calculated directly from crash prediction models.
- Single-vehicle crash frequency: Calculated as the difference between total crash frequency and multiple-vehicle crash frequency. Single-vehicle crashes are always greater than or equal to zero.
- Fatal-and-injury crash frequency: Calculated by taking total crash frequency model and multiplying by combined proportion of K, A, B, and C, crashes from the SDF.
- Property-damage-only crash frequency: Calculated by taking the total crash frequency model and multiplying by the proportion of property-damage-only crashes from the SDF.
- Crash frequency by individual severity level: Calculated by multiplying the total crash frequency by the crash severity proportion from the SDF.
- Crash frequency by crash type: Calculated by multiplying the total crash frequency by the proportion of crashes by crash type.

If an existing freeway facility is being analyzed and historical crash data are available, the EB method should be used to improve the reliability of the computed average crash frequency. The EB method combines model predictions and site-specific crash data in proportion to the level of uncertainty that can be attached to each. Appendix B of the HSM Supplement (*2*) describes the EB method and Chapter 2 of this document includes overdispersion parameters for each crash prediction model that are necessary to perform EB analysis. The EB method would be applicable to a proposed project to convert an existing lane to an HOV or HOT lane.

The predictive method described in Chapter 2 of this document can be used to evaluate a freeway facility with one or more HOV or HOT lanes. The predictive method provided in Chapter 18 of the supplement to the HSM (*2*) can be used to evaluate a freeway facility without HOV or HOT lanes. Together, they can be used to evaluate the change in crash potential associated with the addition of an HOT or HOT lane. However, the predictive models provided in Chapter 18 and those described in this document were developed using data from freeways in different states and different time periods. When the predictions from these models are to be compared or combined, both sets of models *must* be calibrated for the region of interest to ensure that the results are reliable.

If local calibration factors are unavailable and all scenarios being considered can be evaluated with the predictive method described in Chapter 2 of this document, then analysts may compare the relative percent differences in predicted crash frequency for alternatives.

Chapter 5. References

1. Himes, S., J. Bonneson, C. Liu, and V. Gayah. *HOT/HOV Freeway Crash Prediction Method for the Highway Safety Manual. Final Report.* NCHRP Project 17-89A. National Cooperative Highway Research Program, Washington, D.C., forthcoming.

2. AASHTO. *Highway Safety Manual Supplement*. American Association of State Highway and Transportation Officials, Washington, D.C., 2014.

3. AASHTO. *A Policy on Geometric Design of Highways and Streets*. 6th Edition. American Association of State Highway and Transportation Officials. Washington, D.C., 2011.

4. AASHTO. *Highway Safety Manual*. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

5. Fitzpatrick, K. and R. Avelar. *Safety Implications of Managed Lane Cross Sectional Elements.* Report FHWA-HOP-16-076. Federal Highway Administration, Washington, D.C., 2016.

6. Himes, S., J. Bonneson, C. Liu, and V. Gayah. *HOV/HOT Informational Guide*. NCHRP Project 17-89A. National Cooperative Highway Research Program, Washington, D.C., forthcoming.