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Calibration of Highway Safety Manual Safety Performance Functions for Freeway Ramp Terminals in Virginia

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Final Report VTRC 23-R17

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
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vtrc.virginiadot.org

Standard Title Page - Report on Federally Funded Project

<table>
<tr><td>1. Report No.:
FHWA/VTRC 23-R17</td><td colspan="2">2. Government Accession No.:</td><td colspan="2">3. Recipient's Catalog No.:</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle:
Calibration of Highway Safety Manual Safety Performance Functions for Freeway Ramp Terminals in Virginia</td><td colspan="2">5. Report Date:
May 2023</td></tr>
<tr><td colspan="2">6. Performing Organization Code:</td></tr>
<tr><td colspan="3">7. Author(s):
Justice Appiah, Ph.D., P.E.</td><td colspan="2">8. Performing Organization Report No.:
VTRC 23-R17</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903</td><td colspan="2">10. Work Unit No. (TRAIS):</td></tr>
<tr><td colspan="2">11. Contract or Grant No.:
119593</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Federal Highway Administration
400 North 8th Street, Room 750
Richmond, VA 23219-4825</td><td colspan="2">13. Type of Report and Period Covered:
Final</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code:</td></tr>
<tr><td colspan="5">15. Supplementary Notes:
This is an SPR-B report.</td></tr>
<tr><td colspan="5">16. Abstract:
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This study conducted systematic calibration of the HSM ramp terminal SPFs to account for conditions in Virginia. This involved determining appropriate multipliers or functions that aligned the expected average crash frequencies estimated using HSM methodologies with field-observed crash frequencies from selected sites. A review of cumulative residual plots for fitted values suggested that using a single calibration factor as a multiplier to adjust the HSM ramp terminal SPF predictions did not provide a good fit to Virginia data. Consequently, calibration functions were developed that provided a better fit of Virginia data to the HSM ramp terminal SPF predictions. Limiting the number of crash modification factors to 3 instead of using all 11 applicable crash modification factors resulted in a marginally better fit of the data.</td></tr>
<tr><td colspan="2">17 Key Words:
Safety Performance Function, Calibration Factor, Calibration Function, Ramp Terminal, Highway Safety Manual</td><td colspan="3">18. Distribution Statement:
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.</td></tr>
<tr><td>19. Security Classif. (of this report):
Unclassified</td><td colspan="2">20. Security Classif. (of this page):
Unclassified</td><td>21. No. of Pages:
34</td><td>22. Price:</td></tr>
</table>

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

FINAL REPORT

CALIBRATION OF HIGHWAY SAFETY MANUAL SAFETY PERFORMANCE FUNCTIONS FOR FREEWAY RAMP TERMINALS IN VIRGINIA

Justice Appiah, Ph.D., P.E.
Associate Principal Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

May 2023
VTRC 23-R17

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ABSTRACT

Chapter 19 of the Highway Safety Manual (HSM) provides safety performance functions (SPFs) for freeway ramps and crossroad terminals. The chapter includes 56 predictive models for ramp terminals characterized by terminal type, intersection control, crash severity, area type, and number of crossroad lanes. These SPFs were developed with data from other states and need to be calibrated to Virginia conditions to ensure that they accurately reflect the driver population and environment. The application of uncalibrated SPFs may produce misleading results, compromise safety outcomes, and lead to inappropriate design decisions.

This study conducted systematic calibration of the HSM ramp terminal SPFs to account for conditions in Virginia. This involved determining appropriate multipliers or functions that aligned the expected average crash frequencies estimated using HSM methodologies with field-observed crash frequencies from selected sites. A review of cumulative residual plots for fitted values suggested that using a single calibration factor as a multiplier to adjust the HSM ramp terminal SPF predictions did not provide a good fit to Virginia data. Consequently, calibration functions were developed that provided a better fit of Virginia data to the HSM ramp terminal SPF predictions. Limiting the number of crash modification factors to 3 instead of using all 11 applicable crash modification factors resulted in a marginally better fit of the data.

FINAL REPORT

CALIBRATION OF HIGHWAY SAFETY MANUAL SAFETY PERFORMANCE FUNCTIONS FOR FREEWAY RAMP TERMINALS IN VIRGINIA

Justice Appiah, Ph.D., P.E.
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INTRODUCTION

The *Highway Safety Manual* (HSM), first published by the American Association of State Highway and Transportation Officials (AASHTO) in 2010 (AASHTO, 2010), facilitates the quantitative safety analysis of highway facilities. The HSM contains procedures that may be used by highway agencies for identifying locations at high risk for crashes, prioritizing the identified locations, recommending possible safety treatments, and evaluating such treatments. Of particular interest is the predictive method for estimating the expected average crash frequency of a network, facility, or individual site.

A critical requirement of the HSM predictive method is the availability of appropriate safety performance functions (SPFs). An SPF is a mathematical relationship between crash frequency and the most significant causal factors (e.g., annual average daily traffic [AADT] and segment length) on the highway. SPFs are very useful tools for determining the predicted average crash frequency of entities such as intersections and roadway segments. Transportation agencies such as the Virginia Department of Transportation (VDOT) may develop SPFs for use with the predictive method based on their own data. Such jurisdiction-specific SPFs are desirable and "are likely to enhance the reliability of the predictive method" (AASHTO, 2010). However, this requires considerable statistical and subject matter expertise to specify and estimate credible SPFs that "fit into the predictive method" (AASHTO, 2010). An alternative approach is to calibrate the predictive models in the HSM.

The HSM contains SPFs for different facility types. Often, these SPFs have been developed using crash data from a subset of states and under a set of roadway and traffic conditions termed "base conditions." Therefore, the predictions made by the SPFs would need to be adjusted appropriately when they are applied to entities with non-base attributes and/or in jurisdictions other than those for which they were developed. The HSM provides a predictive modeling process that may be used to accomplish this. In particular, the HSM SPF serves as a base model used to determine the predicted average crash frequency for base conditions; crash modification factors (CMFs) are used as multipliers to account for specific geometric and operational conditions that differ from base conditions; and a local calibration factor is used to account for differences in factors such as climate, crash reporting thresholds, and driver population between the jurisdiction where the SPFs are to be applied and those for which the models were developed.

In 2014, AASHTO released a supplement to the HSM that includes SPFs for freeways (freeway segments, speed-change lanes) and ramps used to connect two or more roadways at an interchange (ramp segments, ramp terminals, and collector-distributor road segments) (AASHTO, 2014). The supplement includes 56 SPFs for ramp terminals characterized by terminal type, intersection control, crash severity, area type (urban or rural), and number of crossroad lanes. The SPFs were developed using data from California, Maine, and Washington and may or may not reflect conditions in Virginia. There is, therefore, a need to calibrate these SPFs to Virginia conditions to ensure that they accurately reflect the driver population and environment.

Accurate SPFs facilitate the quantitative safety analysis of highway facilities and can be used to make better safety decisions. Calibration is important because safety conditions may differ significantly among jurisdictions, as well as change over time. The application of uncalibrated SPFs may produce misleading results, compromise safety outcomes, and lead to inappropriate design decisions.

PURPOSE AND SCOPE

The purpose of this study was to conduct systematic calibration of the HSM freeway ramp terminal SPFs to account for conditions in Virginia. This involved the estimation of a calibration factor or function and the estimation of a dispersion parameter. The calibrated dispersion parameter is required for use of the empirical Bayes procedure discussed in the HSM (Lyon et al., 2016).

The scope included calibration of the following:

- SPFs for individual ramp terminal configuration types distinguished by cross section, intersection control, area type, and crash severity
- SPFs for stop-controlled ramp terminals (as a group) distinguished by crash severity
- SPFs for signal-controlled ramp terminals (as a group) distinguished by crash severity.

BACKGROUND

An essential part of the HSM quantitative safety analysis methodology is the use of predictive models to determine the predicted average crash frequency on various highway facilities, including freeway ramp terminals. This section provides an overview of the predictive model as pertains to ramp terminals to provide background and context for the remainder of the report.

The predictive models are of the general form shown in Equation 1. It consists of three basic elements: (1) a base model, (2) a set of CMFs, and (3) a calibration factor or function.

$$N_p = N_{spf} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_m) \times C \qquad \text{[Eq. 1]}$$

where

N_p = predicted average crash frequency (crashes/year)

N_{spf} = predicted average crash frequency determined for base conditions from the SPF

$CMF_1 \ldots CMF_m$ = a set of crash modification factors or functions to account for site-specific geometric and operational conditions

C = calibration factor or function to adjust for jurisdictional differences.

Base Model

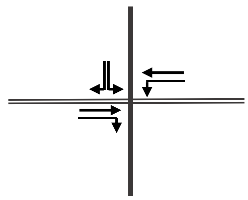
The base model is an SPF developed under a set of roadway and traffic conditions termed "base conditions." For the signal-controlled ramp terminal SPFs in the HSM (AASHTO, 2014), these conditions include the following:

- absence of left-turn and right-turn lanes on the crossroad
- absence of a public street approach or driveway
- no adjacent ramp or public street intersection within 6 mi
- presence of a 12-ft median on the crossroad
- absence of protected left-turn phasing on the crossroad
- absence of channelized right-turn on crossroad and exit ramp
- absence of a non-ramp public street leg at terminal.

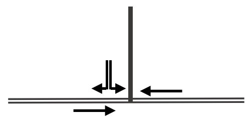
Base conditions for stop-controlled terminals include the following:

- absence of left-turn and right-turn lanes on the crossroad
- absence of a public street approach
- no adjacent ramp or public street intersection within 6 mi
- presence of a 12-ft median on the crossroad
- zero skew angle.

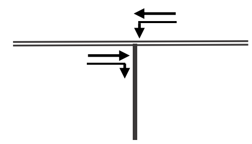
The HSM contains base SPF models for seven freeway ramp terminal configurations as shown in Figure 1. The configurations are distinguished by differences in three attributes: (1) number of ramp legs, (2) number of left-turn movements, and (3) location of crossroad left-turn storage (inside or outside the interchange) (AASHTO, 2014). There are 56 ramp terminal SPFs (base models) characterized by terminal type, intersection control, cross section, area type (urban or rural), and crash severity. Table 1 summarizes the ramp terminal SPFs in the HSM.



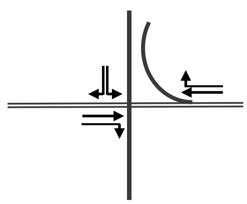
(a) Four-leg ramp terminal with diagonal ramps (*D4*)



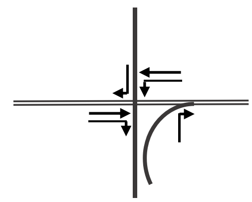
b) Three-leg ramp terminal with diagonal exit ramp (*D3ex*)



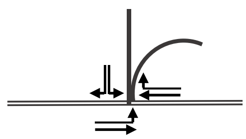
c) Three-leg ramp terminal with diagonal entrance ramp (*D3en*)



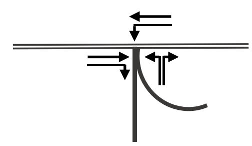
d) Four-leg ramp terminal at four-quadrant partial cloverleaf A (*A4*)



e) Four-leg ramp terminal at four-quadrant partial cloverleaf B (*B4*)



f) Three-leg ramp terminal at two-quadrant partial cloverleaf A (*A2*)



g) Three-leg ramp terminal at two-quadrant partial cloverleaf B (*B2*)

Figure 1. Schematic Diagram of Ramp Terminal Configurations. In each case, the crossroad is depicted with a double line running east-west and ramps are shown with solid lines; the freeway (not shown) is to the right.

The general form of the HSM ramp terminal SPFs is shown in Equation 2.

$$N_{spf} = exp\left(\beta_0 + \beta_1 ln\left[\frac{AADT_{xrd}}{1000}\right] + \beta_2 ln\left[\frac{AADT_{ex}}{1000} + \frac{AADT_{en}}{1000}\right]\right) \quad \text{[Eq. 2]}$$

where

N_{spf} = predicted average crash frequency for base conditions (crashes/year)

β_0, β_1, β_2 = regression coefficients (see HSM references in Table 1 for coefficient values)

$AADT_{ex}$ = AADT on exit ramp

$AADT_{en}$ = AADT on entrance ramp

$AADT_{xrd}$ = AADT on crossroad, defined as shown in Equation 3.

$$AADT_{xrd} = 0.5 \times (AADT_{in} + AADT_{out}) \quad \text{[Eq. 3]}$$

where

$AADT_{in}$ = AADT on crossroad leg between ramps
$AADT_{out}$ = AADT on crossroad leg outside interchange.

Table 1. Highway Safety Manual Ramp Terminal Safety Performance Functions

<table>
<tr><th>Ramp Terminal Type</th><th>Cross Section and Control Type</th><th>Area Type</th><th>Crash Severity</th><th>Highway Safety Manual Reference</th></tr>
<tr><td rowspan="14">Three-leg terminal at two-quadrant partial cloverleaf A or B</td><td rowspan="2">One-way stop control; 2-, 3-, or 4-lane crossroad</td><td rowspan="2">Urban</td><td>FI</td><td rowspan="4">Table 19-17</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">One-way stop control; 2-, 3-, or 4-lane crossroad</td><td rowspan="2">Rural</td><td>FI</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">Signal control; 2-lane crossroad</td><td rowspan="2">Rural or urban</td><td>FI</td><td rowspan="10">Table 19-12</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">Signal control; 3-lane crossroad</td><td rowspan="2">Rural or urban</td><td>FI</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">Signal control; 4-lane crossroad</td><td rowspan="2">Rural or urban</td><td>FI</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">Signal control; 5-lane crossroad</td><td rowspan="2">Urban</td><td>FI</td></tr>
<tr><td>PDO</td></tr>
<tr><td rowspan="2">Signal control; 6-lane crossroad</td><td rowspan="2">Urban</td><td>FI</td></tr>
<tr><td>PDO</td></tr>
<tr><td colspan="4">*Three-leg terminal with diagonal exit ramp or four-leg terminal at four-quadrant partial cloverleaf A</td><td>Table 19-18; Table 19-13</td></tr>
<tr><td colspan="4">*Three-leg terminal with diagonal entrance ramp or four-leg terminal at four-quadrant partial cloverleaf B</td><td>Table 19-19; Table 19-14</td></tr>
<tr><td colspan="4">*Four-leg terminal with diagonal ramps</td><td>Table 19-20; Table 19-15</td></tr>
</table>

FI = fatal and injury crashes; PDO = property damage only crashes.
*These types have the same combination of safety performance functions based on cross section and control type, area type, and crash severity as the three-leg terminal at two-quadrant partial cloverleaf A or B. The table was truncated for brevity.

Crash Modification Functions

Because the ramp terminal SPFs have been developed for specific base geometric and operational conditions, the predictions need to be adjusted appropriately when the SPFs are used for facilities with non-base attributes. In this regard, the HSM ramp terminal SPFs include a set of CMFs that may be used to determine relevant adjustment factors needed to account for specific site conditions that may vary from the base conditions. Table 2 is a summary of the ramp terminal CMFs and the SPFs to which they are applicable. For brevity, the specific CMF equations are not provided in this report; instead, Table 2 shows relevant portions of the HSM where they may be found (AASHTO, 2014).

Table 2. Ramp Terminal Crash Modification Functions

Crash Modification Factor	Applicable Safety Performance Function			Highway Safety Manual Reference
	Control	Area Type	Crash severity	
CMF$_{10}$: Exit ramp capacity	One-way stop control	Rural or urban	FI	Equation 19-42; Table 19-32
	Signal control	Rural or urban	FI	
CMF$_{11}$: Crossroad left-turn lane[a]	One-way stop control	Rural	FI	Equation 19-45; Table 19-33
			PDO	
		Urban	FI	
			PDO	
	Signal control	Rural	FI	
			PDO	
		Urban	FI	
			PDO	
CMF$_{13}$: Access point frequency[b]	One-way stop control	Rural or urban	FI	Equation 19-49; Table 19-35
	Signal control	Rural or urban	FI	
			PDO	
CMF$_{16}$: Protected left-turn operation[c]	Signal control	Rural or urban	FI	Equation 19-53; Table 19-38
		Rural or urban	PDO	
CMF$_{20}$: Skew angle	One-way stop control	Rural or urban	FI	Equation 19-58
CMF$_{12}$: Crossroad right-turn lane[a]				Equation 19-47; Table 19-34
CMF$_{14}$: Segment length[b]				Equation 19-50; Table 19-36
CMF$_{15}$: Median width[b]				Equation 19-51; Table 19-37
CMF$_{17}$: Channelized right turn on crossroad[c]				Equation 19-55; Table 19-39
CMF$_{18}$: Channelized right turn on exit ramp[c]				Equation 19-56; Table 19-40
CMF$_{19}$: Non-ramp public street leg[c]				Equation 19-57; Table 19-41

FI = fatal and injury crashes; PDO = property damage only crashes.
[a, b, c] Crash modification factors with identical superscripts share the same combination of applicable safety performance functions based on control type, area type, and crash severity. The table was truncated for brevity.

Calibration Factor or Function

The third component of the HSM predictive models is the calibration factor or function. The calibration factor is used to account for differences in crash reporting thresholds, driver population, topology, climate, etc., between the jurisdictions or states for which the models were developed and the jurisdiction or state where they are being applied. A calibration factor is calculated as the ratio of the summation of observed crashes for a select set of sites in the jurisdiction of interest to the summation of predicted crashes for the same set of sites (AASHTO, 2010). A calibration factor greater than 1.0 would suggest more crashes, on average, in the study jurisdiction than in the jurisdiction for which the models were developed, whereas a factor less than 1.0 would suggest fewer crashes, on average. The HSM recommends that new values of the calibration factor be derived at least every 2 to 3 years. Further, the HSM recommends that a minimum of 30 to 50 sites be used to calibrate the predictive model.

A calibration factor serves as a multiplier to adjust the model predictions up or down. It is conceivable that a calibration factor closer to 1.0 may be determined and yet not provide a good fit to local data. A calibration function is a more flexible alternative and may be considered when the single multiplier does not provide a good fit. A calibration function provides a unique calibration factor for each site depending on site-specific values of the inputs (Bahar and Hauer, 2014; Rajabi et al., 2018; Srinivasan et al., 2016).

METHODS

Six tasks were performed to achieve the objectives of the study.

1. Identify ramp terminal types.
2. Identify calibration sites.
3. Collect data.
4. Predict crash frequencies.
5. Derive and assess calibration factors.
6. Derive and assess calibration functions.

Task 1: Identification of Terminal Types

The roadway network in Virginia was reviewed to identify sites for possible inclusion in the study. An inventory of applicable terminal configurations, characterized by configuration type and latitude-longitude coordinates, was created by viewing images (in Google Earth or Google Maps) of ramp terminal junctions along the interstate highway network for those that fit the schematic diagrams shown in Figure 1. This inventory served as the sampling frame from which sites were selected for calibration.

Task 2: Identification of Calibration Sites

Sites were identified that satisfied the sample size requirements needed to calibrate the predictive models as specified in the HSM. In particular, the HSM states that a minimum of 30 to 50 sites are needed for calibration. For a given site type, the HSM also recommends that the calibration database (assembled from the sample of calibration sites) include at least 100 target crashes per year. These sample size constraints meant that not every one of the 56 ramp terminal SPFs available in the HSM could be calibrated. The scope of the study was limited to those SPFs for which sufficient data were available.

The HSM predictive method also allows for grouping ramp terminal SPFs into four groups based on control type (stop vs. signal) and injury severity (fatal and injury [FI] vs.

property damage only [PDO]) and developing a single calibration factor for each group, rather than developing calibration factors for all 56 SPFs. This study developed calibration factors and functions for the four SPF groupings and for individual SPFs for which data were available at a sufficient number of sites.

Task 3: Collection of Data

The data needed to calibrate a predictive model or group of predictive models (SPF grouping) were assembled. Data were collected for the 3 years 2018, 2019, and 2021. Data for year 2020 were excluded from the study because of disruptions to traffic flow caused by the COVID-19 pandemic and related business closures (Goenaga et al., 2021). Three main types of data were collected: site geometric and operational data, AADT data, and crash data.

Geometric and Operational Data

Several pieces of detailed geometric and operational data were collected for the calibration sites identified in Task 2. These data were primarily used as inputs to the CMFs that accompany the HSM ramp terminal SPFs. The specific variables collected at each site were as follows:

Geometric Data

- Number of lanes on the exit ramp
- Number of through lanes on each crossroad approach
- Presence of left-turn lane on each crossroad approach
- Presence of right-turn lane on each crossroad approach
- Presence of right-turn channelization on each crossroad approach
- Presence of right-turn channelization on the exit ramp
- Crossroad median width
- Width of left-turn lane on each crossroad approach
- Skew angle between exit ramp and crossroad.

Operational Data

- Type of traffic control at the terminal
- Exit ramp right-turn control type
- Presence of protected left-turn operation on each crossroad approach
- Distance to next public street intersection
- Distance to adjacent ramp terminal
- Number of unsignalized public street approaches to the crossroad leg outside the interchange
- Number of unsignalized driveways on the crossroad leg outside the interchange.

An initial review did not identify a readily available source for these variables at the level of detail needed within VDOT. Therefore, the data were collected almost exclusively by reviewing Google Earth (and Google Maps) images for the terminal locations. Information regarding the presence of protected left-turn phasing on the crossroad approaches was provided by VDOT field engineers and supplemented by Google Earth images; for example, the left-turn movement from an approach with a "Left-Turn Yield on Flashing Yellow Arrow" sign would be considered not protected.

A geospatial dataset was created that consisted of a unique identification (ID) for each terminal, the terminal's configuration type and geographic coordinates (from Task 1), and the geometric and operational variables collected in this task. All spatial analyses in this study were done using GeoPandas, a Python module based on the Pandas library that facilitates geospatial data analysis in Python.

Annual Average Daily Traffic Data

For each ramp terminal, AADT data were collected for the exit ramp, entrance ramp, crossroad leg between ramps, and crossroad leg outside the interchange. AADT data were collected from VDOT sources in two steps.

First, the unique link ID associated with each ramp terminal leg in VDOT's databases was identified. This was done in GeoPandas by drawing 100- to 500-ft buffers around the ramp terminal locations and spatially joining them to a geodatabase of the VDOT network that contained link ID and other pertinent information such as the names of the links and their start and end labels/names. All link IDs identified as being associated with a terminal were manually reviewed to ensure correct assignment to the ramp terminal legs.

Second, with the link ID information known for the exit ramp, entrance ramp, inside crossroad leg, and outside crossroad legs, AADTs were retrieved from the VDOT Traffic Monitoring System (TMS) database using the link IDs as the key. The link ID information was also used to obtain the rural-urban designation (area type) of each terminal from the VDOT Traffic Operations Division's Oracle database (COTEDOP).

Crash Data

Crash data were obtained from Virginia Roads, VDOT's open access data portal. The crash records included unique ID, year, severity, route name and milepost, and latitude-longitude coordinates. Crashes were assigned to terminals using the GeoPandas nearest-neighbor spatial join feature. The nearest-neighbor algorithm queried distances between the crash locations and the terminal locations. A crash was assigned to a terminal if the distance between these locations was the smallest within a range of 250 ft. The use of a 250-ft radius is common practice for safety data analysis within VDOT. In addition, the HSM notes that ramp terminals separated by more than 250 ft should be treated as separate entities for analysis (AASHTO, 2014). Crashes within the 250-ft radius were excluded if they occurred on the main freeway lanes (see Figure 2). Crash data were aggregated at each terminal by severity (FI vs. PDO) and year.

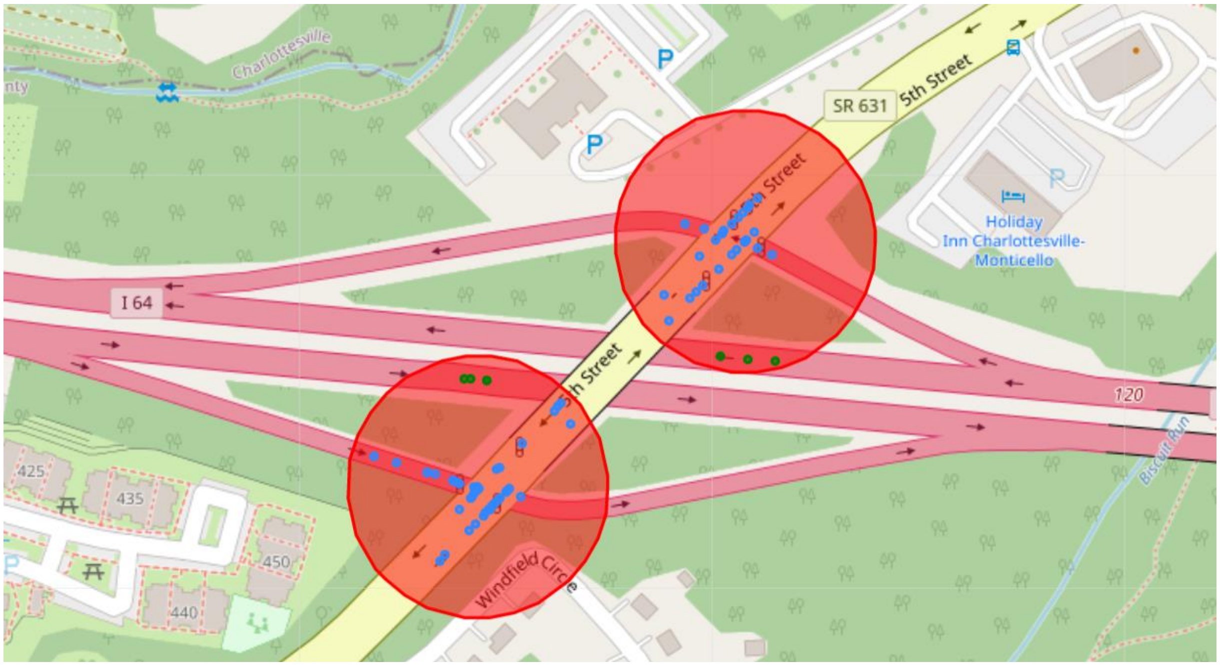


Figure 2. Assignment of Crashes to Ramp Terminals. Note that crashes within a 250-ft radius of the terminal were assigned to the terminal (shown as blue circle markers); crashes that occurred on the main freeway lanes (shown as green circle markers) were excluded.

The dataset assembled in this task was formatted such that there were six records for each terminal—one for each analysis year–crash severity combination. Each record included the terminal ID, configuration, AADT, crash count, crash severity, year, area type, and geometric and operational variables.

Task 4: Prediction of Average Crash Frequencies

The data assembled in Task 3 were used to determine average crash frequencies based on the HSM predictive model. No calibration factor was used in this task (assumed $C = 1$). This task was accomplished through three subtasks:

1. *Identification of SPFs and SPF groupings*. First, the SPF and SPF grouping appropriate for each record in the dataset was identified. Each record was assigned an SPF based on the values of its control type, number of crossroad lanes, area type, and crash severity fields (see Table 1). Similarly, SPF groupings were assigned based on the control type and crash severity fields.

2. *Calculation of crash modification factors*. Next, the data were aggregated by terminal ID and crash severity such that there were then two records for each terminal. AADTs were replaced with the 3-year average and crash counts were replaced by the sum over the 3-year analysis period. This was consistent with the approach adopted by the Federal Highway Administration's *Calibrator* tool (Lyon et al., 2016). Python functions were developed for each of the 11 ramp terminal CMFs shown in Table 2. The functions were used to calculate the value of each CMF for

each record depending on the site-specific data pertaining to that record. The product of applicable CMF values for each record was determined for later use in the predictive model.

3. *Exploration of the use of a limited number of CMFs*. The study's technical review panel expressed concern about the potential impact of using a large number of CMFs (in this case up to 11), especially because they are multiplicative. Similar concerns have been raised in the literature by others, and several potential remedies have been proposed including limiting the number of CMFs to 2 or 3 (Carter et al., 2021). This subtask explored the merits of limiting the number of CMFs to 3 through bootstrap resampling. That is, for each record in the dataset, a maximum of 3 CMFs at a time were repeatedly drawn with replacement from all the applicable CMFs and the product of the selected CMFs was calculated each time. In each case, the expected value of the product of CMFs was estimated as the mean of 10,000 bootstrap resamples.

4. *Determination of average crash frequencies*. In this subtask, the HSM-predicted average crash frequencies, N_{HSM}, were determined. This was calculated for each record in the dataset using Equation 4, which is derived by setting the calibration factor in Equation 1 equal to 1, so that

   $$N_{HSM} = N_{spf} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_m) \quad \text{[Eq. 4]}$$

   where N_{spf} and $CMF_1, \ldots, CMF_m$ are as previously defined in Equation 1.

   Values of N_{HSM} were calculated with the product determined with both the full set of CMFs (Step 2; m = 11) and the truncated set (Step 3; m = 3). The predicted average crash frequency for each record was multiplied by 3 (the number of years of data) to obtain an estimate of the predicted number of crashes for the study period (with no calibration).

Task 5: Derivation and Assessment of Calibration Factors

In this task, calibration factors and relevant dispersion parameters needed for use of the empirical Bayes procedure described in the HSM were estimated. The calibration factor for each SPF or SPF grouping was determined as shown in Equation 5 by dividing the sum of observed crashes (over all applicable sites/records) by the sum of predicted crashes (for the same set of sites).

$$C = \frac{\sum_{i=1}^{n} N_{oi}}{T \times \sum_{i=1}^{n} N_{HSMi}} \quad \text{[Eq. 5]}$$

where

N_{oi} = observed number of crashes at site i for the entire study period

N_{HSMi} = HSM-predicted average crash frequency (uncalibrated) at site i (crashes/year)

T = number of years of data used for calibration

n = number of sites in the calibration dataset for which the SPF or SPF grouping is applicable.

With the calibration factor known, the predicted average crash frequency (calibrated) at a site, N_p, could be calculated using Equation 1.

Dispersion parameters were estimated for each SPF and SPF grouping through maximum likelihood estimation assuming a negative binomial distribution of the errors. Specifically, a Python script was created to maximize the negative binomial likelihood function (see Equation 6) and thus determine the dispersion parameter value that maximized the likelihood of the calibration data (Spiegelman et al., 2010).

$$L(k) = \prod_{i=1}^{n} \frac{\Gamma(k^{-1}+N_{oi})}{\Gamma(k^{-1})\Gamma(N_{oi}+1)} \left(\frac{k^{-1}}{T\times N_{pi}+k^{-1}}\right)^{1/k} \left(\frac{T\times N_{pi}}{T\times N_{pi}+k^{-1}}\right)^{N_{oi}} \quad \text{[Eq. 6]}$$

where L is the likelihood function, k is the dispersion parameter, and other variables are as previously defined.

The quality of the calibration was assessed using the following three goodness-of-fit (GOF) measures (Lyon et al., 2016):

1. *Mean absolute deviation (MAD).* The MAD measures the average magnitude of the errors in the predictions. Smaller values are desirable. The MAD was calculated as shown in Equation 7:

$$MAD = \frac{\sum_{i=1}^{n} |T\times N_p - N_o|}{n} \quad \text{[Eq. 7]}$$

2. *Coefficient of variation (CV).* The CV of the calibration factor is the ratio of the standard deviation to the estimated value of the calibration factor. In general, a lower CV is indicative of a good fit. According to Bahar and Hauer (2014), a CV of 0.10 to 0.15 may suggest that the estimated calibration factor is acceptable. The CV was calculated as shown in Equation 8:

$$CV = \frac{\sqrt{V(C)}}{C} \quad \text{[Eq. 8]}$$

where *V(C)* is the variance of the calibration factor, defined as shown in Equation 9.

$$V(C) = \frac{\sum_{i=1}^{n}(N_{oi}+k\times N_{oi}^2)}{\left(\sum_{i=1}^{n} N_{HSMi}\right)^2} \quad \text{[Eq. 9]}$$

All variables are as previously defined.

3. *Cumulative residual (CURE) plots*. The quality of the calibration was also assessed by developing and reviewing plots of the cumulative residuals (observed minus predicted crashes) against the fitted values (after the calibration factor was applied). According to Lyon et al. (2016), this is "the most objective consideration" for assessing the quality of calibration. In particular, the CUREs are approximately normally distributed (Hauer and Bamfo, 1997) so that "an upper threshold of five percent of CURE plot ordinates for fitted values exceeding the 95% percent confidence limits is indicative of an SPF that calibrates well to the entire range of a jurisdiction's data." The procedure for developing CURE plots is described in Hauer and Bamfo (1997); a detailed step-by-step process including how to create 95% confidence limits is provided in Lyon et al. (2016). These steps were followed to develop CURE plots for this study.

Task 6: Derivation and Assessment of Calibration Functions

The CURE plots may indicate that single calibration factors like those estimated in Task 5 are not appropriate to calibrate adequately the HSM ramp terminal SPFs to Virginia conditions. Therefore, this task explored the development of calibration functions that might provide a better fit to the data than the single calibration factors developed in Task 5. The quality of fit was assessed using CURE plots as the primary tool.

The general form of the calibration function adopted for this study is as shown in Equation 10.

$$N_p = a \times (N_{HSM})^b \qquad \text{[Eq. 10]}$$

where a and b are regression coefficients and all other variables are as previously defined.

The form of the calibration function specified in Equation 10 is widely accepted partly because it is simple and intuitively appealing; in particular, the parameter a logically equals the calibration factor when b equals 1 (Claros et al., 2020; Matarage and Dissanayake, 2020; Srinivasan et al., 2016).

To estimate a calibration function, a negative binomial regression model was fit to the calibration data using the observed crash frequency as the dependent variable and the HSM-predicted (uncalibrated) average crash frequency as the predictor variable.

RESULTS

Data

HSM calibration is a data-intensive process that uses three main types of data: geometric and operational, AADT, and crash data. Geometric and operational data including median width, number of driveways, exit ramp right-turn control type, etc., were obtained primarily by a review of Google Earth images. AADT and crash data were obtained from VDOT sources. AADT data were collected for the entrance and exit ramps and the crossroad legs inside and outside the interchange.

SPFs and Calibration Sites

The analysis was restricted to terminals for which AADT data were available for all legs throughout the analysis period. The initial inventory consisted of 388 ramp terminal locations. Of these, 38 were excluded from the analysis because they were missing link ID information needed to retrieve AADT data or they did not have AADT data for all analysis years. In addition, the HSM ramp terminal SPFs are applicable over a defined range of AADTs (AASHTO, 2014). Therefore, another 14 terminal locations at which some or all of the legs had AADTs greater than the maximums specified in the HSM were discarded. The final dataset included 336 terminals, 236 (approximately 70%) of which were stop controlled. Table 3 summarizes the HSM SPFs and the number of sites in the dataset available for calibration. The number of sites available for calibrating the SPF groupings is also shown in the table in the last four rows.

There were no data available for 10 of the 56 SPFs. For the 46 SPFs with data available, only 2 met the HSM recommendation of at least 30 sites with 100 or more target crashes per year needed for calibration. Both of those SPFs were for PDO crashes only. The corresponding numbers of FI crashes at the two sets of sites did not meet the HSM's threshold of 100 target crashes per year. However, because FI crash data tend to be more reliable than data for PDO crashes, the FI SPFs for these two sets of sites were also selected for calibration. Thus, the calibration effort was limited to the following 4 individual SPFs and 4 SPF groupings (distinguished only by control type and crash severity):

- FI crash SPF for rural one-way stop-controlled four-leg terminal with diagonal ramps (D4) and 2, 3, or 4 crossroad lanes

- PDO crash SPF for rural one-way stop-controlled four-leg terminal with diagonal ramps (D4) and 2, 3, or 4 crossroad lanes

- FI crash SPF for rural or urban signalized four-leg terminal with diagonal ramps (D4) and 4 crossroad lanes

- PDO crash SPF for rural or urban signalized four-leg terminal with diagonal ramps (D4) and 4 crossroad lanes

- FI crash SPF for one-way stop-controlled ramp terminals (all configurations, area types, and crossroad lanes)

- PDO crash SPF for one-way stop-controlled ramp terminals (all configurations, area types, and crossroad lanes)

- FI crash SPF for signal-controlled ramp terminals (all configurations, area types, and crossroad lanes)

- PDO crash SPF for signal-controlled ramp terminals (all configurations, area types, and crossroad lanes).

Calibration Data Summary

Tables 4 and 5 summarize the crash and AADT data used to calibrate the SPFs and SPF groupings identified in the previous section. As expected, the average crossroad and ramp AADTs were higher for the signalized terminals than they were for the stop-controlled terminals. There were also more total crashes per site-year at the signalized terminals than at the stop-controlled terminals, which was also not surprising because of higher traffic volumes at the signalized terminals. Approximately 65% of all crashes in the calibration dataset were PDO crashes. This was the case for both the stop-controlled and signal-controlled terminals.

Table 6 shows the products of the CMFs, which quantify the overall adjustments needed to account for geometric and operational conditions at the calibration sites that differed from the base conditions for which the HSM SPFs were developed. The values in Table 6 (see Column 7) suggest that, on average, the base SPF models over-predict crashes at the calibration sites; the values in Column 7 would be 1.0 if there was no over- or under-prediction. For instance, the table shows that adjusting for site-specific conditions at signal-controlled terminals with all applicable CMFs reduced the base SPF prediction by an average of 13% and 2% for FI and PDO crashes, respectively. For signalized four-legged terminals with diagonal ramps and four crossroad lanes, application of the CMFs reduced the base predictions by 25% and 14% for FI and PDO crashes, respectively. In general, the magnitudes of the average reductions to the base SPF predictions were relatively smaller when the number of CMFs was limited to three. Nevertheless, they still indicated that the base SPFs tend to over-predict crashes at the calibration sites and thus highlight the need to adjust for site-specific conditions when the ramp terminal SPFs in the HSM are used.

Table 3. Number of Sites Available by Ramp Terminal Safety Performance Function

Terminal Type	Control Control Type	No. of Crossroad Lanes	Area Type	Crash Severity	No. of Sites	Crashes per Year
Three-leg terminal at two-quadrant partial cloverleaf A or B	One-way stop control	2, 3, 4	Urban	FI	4	2.0
				PDO	4	7.3
			Rural	FI	10	6.3
				PDO	10	6.3
	Signal control	2	Rural or Urban	FI	1	3.3
				PDO	1	0.7
		3	Rural or Urban	FI	2	2.7
				PDO	2	4.7
		4	Rural or Urban	FI	5	8.0
				PDO	5	33.0
		6	Urban	FI	2	1.7
				PDO	2	6.0
Three-leg terminal with diagonal exit ramp or four-leg terminal at four-quadrant partial cloverleaf A	One-way stop control	2, 3, 4	Urban	FI	7	3.7
				PDO	7	6.0
			Rural	FI	8	3.3
				PDO	8	4.0
	Signal control	2	Rural or Urban	FI	3	6.0
				PDO	3	5.3
		3	Rural or Urban	FI	1	0.0
				PDO	1	0.7
		4	Rural or Urban	FI	19	50.3
				PDO	19	73.7
		5	Urban	FI	2	8.7
				PDO	2	8.7
		6	Urban	FI	1	2.0
				PDO	1	2.3
Three-leg terminal with diagonal entrance ramp or four-leg terminal at four-quadrant partial cloverleaf B	One-way stop control	2, 3, 4	Urban	FI	13	8.7
				PDO	13	14.3
			Rural	FI	9	1.0
				PDO	9	3.3
	Signal control	2	Rural or Urban	FI	1	0.0
				PDO	1	0.7
		4	Rural or Urban	FI	5	13.3
				PDO	5	23.0
Four-leg terminal with diagonal ramps	One-way stop control	2, 3, 4	Urban	FI	38	24.3
				PDO	38	43.7

			Rural	FI*	147	51.3
				PDO*	147	100.3
	Signal control	2	Rural or Urban	FI	15	11.3
				PDO	15	41.3
		3	Rural or Urban	FI	3	3.7
				PDO	3	8.3
		4	Rural or Urban	FI*	37	70.0
				PDO*	37	122.0
		5	Urban	FI	3	9.0
				PDO	3	23.0
All	One-way stop control	2, 3, 4	Rural or Urban	FI+	236	100.7
				PDO+	236	185.3
All	Signal control	2 to 6	Rural or Urban	FI+	100	190.0
				PDO+	100	353.3

FI = fatal and injury crashes; PDO = property damage only crashes.
*Individual SPFs selected for calibration.
+SPF groupings to be calibrated.

Table 4. Summary of Crash and Crossroad Traffic Volume Data

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	No. of Sites	Crashes per Year	Crossroad Traffic (veh/day)		
						Min.	Max.	Mean
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	147	51.3	34	13210	4000
			PDO	147	100.3	34	13210	4000
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	37	70.0	2883	40032	16448
			PDO	37	122.0	2883	40032	16448
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	236	100.7	34	19906	4863
			PDO	236	185.3	34	19906	4863
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	100	190.0	2384	40032	15526
			PDO	100	353.3	2384	40032	15526

Min. = minimum; Max. = maximum; FI = fatal and injury crashes; PDO = property damage only crashes.
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Table 5. Summary of Ramp Traffic Volume Data

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Entrance Ramp Traffic (veh/day)			Exit Ramp Traffic (veh/day)		
				Min.	Max.	Mean	Min.	Max.	Mean
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	36	7243	1531	43	5804	1385
			PDO	36	7243	1531	43	5804	1385
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	1807	11737	4833	1337	11398	4974
			PDO	1807	11737	4833	1337	11398	4974
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	36	7243	1797	43	6684	1636
			PDO	36	7243	1797	43	6684	1636
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	755	13941	4858	1109	11398	5186
			PDO	755	13941	4858	1109	11398	5186

FI = fatal and injury crashes; PDO = property damage only crashes; Min. = minimum; Max. = maximum.

Table 6. Summary of Products of Crash Modification Factors

Terminal Type (1)	Cross Section and Control Type (2)	Area Type (3)	Crash Severity (4)	Up To 11 CMFs*			Up To 3 CMFs*		
				Min. (5)	Max. (6)	Mean (7)	Min. (8)	Max. (9)	Mean (10)
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	0.44	1.94	0.88	0.48	2.09	0.95
			PDO	0.68	1.14	0.91	0.68	1.14	0.91
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	0.25	1.09	0.75	0.49	1.25	0.81
			PDO	0.30	1.99	0.86	0.36	2.42	0.93
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	0.44	3.08	0.92	0.47	2.45	0.96
			PDO	0.67	1.26	0.90	0.67	1.26	0.90
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	0.22	3.55	0.87	0.24	2.24	0.88
			PDO	0.28	4.92	0.98	0.32	2.42	0.91

FI = fatal and injury crashes; PDO = property damage only crashes; Min. = minimum; Max. = maximum.
*CMF = crash modification factor. "Up to 11 CMFs" indicates the product of all applicable *Highway Safety Manual* (HSM) CMFs. "Up to 3 CMFs" indicates the product of up to 3 CMFs selected via bootstrap resampling of the applicable HSM CMFs. Values shown are averages for all relevant sites.

SPF Calibration

This section presents the results of the calibration factor and function development.

Predicted Crashes

An initial step in the calibration process was to determine predicted average crash frequencies at all calibration sites. For each site, the compiled AADT and crash data were used to determine a predicted crash frequency for base conditions using the applicable base SPF model (Table 1), which was then multiplied by applicable CMFs (Table 2) to account for site-specific geometric and operational conditions. Another set of predicted average crash frequencies were also calculated with the same approach except that the number of CMFs was limited to three. The three CMFs used for each site were obtained through bootstrap resampling of the applicable CMFs. The predicted crash frequencies are shown in Table 7.

The predicted crash frequency was highest for PDO crashes at signal-controlled terminals with 3.5 crashes per site-year and lowest for FI crashes at stop-controlled terminals with 0.35 crashes per site-year. The trend was similar for predicted crash frequencies determined using up to three CMFs and for the observed crash frequencies. Predicted crashes were generally lower than observed crashes at stop-controlled terminals and the reverse was generally true for signalized ramp terminals.

Table 7. Predicted Crashes by Safety Performance Function

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Σ(Observed Crashes)	Σ(Predicted Crashes)	
					With Up to 11 CMFs	With Up to 3 CMFs
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	154	136	144
			PDO	301	201	201
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	210	310	343
			PDO	366	458	505
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	302	252	258
			PDO	556	379	379
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	570	735	779
			PDO	1060	1060	1019

FI = fatal and injury crashes; PDO = property damage only crashes.

Calibration Factor Results

A calibration factor was calculated for each SPF and SPF grouping by dividing the sum of observed crashes at all applicable sites by the sum of the SPF-predicted crashes at the same set of sites. The results including the recalibrated dispersion parameter and other GOF measures are summarized in Tables 8 and 9. All calculations were done using Python scripts in accordance with the methodology described earlier and detailed in Lyon et al. (2016).

Table 8. Calibration Factors for Ramp Terminal Safety Performance Functions Determined Using All Applicable Crash Modification Factors

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Calibration Factor	Dispersion Parameter*	Goodness-of-Fit: Mean Absolute Deviation	Goodness-of-Fit: Coefficient of Variation	Goodness-of-Fit: CURE Deviation+
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	1.14	0.24	0.78	0.11	13%
			PDO	1.50	0.57	1.50	0.11	61%
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	0.68	0.56	3.64	0.18	8%
			PDO	0.80	0.36	5.13	0.14	3%
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	1.20	0.72	1.05	0.12	65%
			PDO	1.47	0.66	1.76	0.09	82%
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	0.78	0.98	3.93	0.14	69%
			PDO	1.00	0.59	5.82	0.10	72%

FI = fatal and injury crashes; PDO = property damage only crashes.
*For use with the empirical Bayes procedure described in the *Highway Safety Manual.*
+Cumulative residual (CURE) plot ordinates for fitted values outside the 95% confidence intervals.

Table 9. Calibration Factors for Ramp Terminal Safety Performance Functions Determined Using Up To Three Applicable Crash Modification Factors

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Calibration Factor	Dispersion Parameter*	Goodness-of-Fit: Mean Absolute Deviation	Goodness-of-Fit: Coefficient of Variation	Goodness-of-Fit: CURE Deviation+
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	1.07	0.35	0.86	0.12	6%
			PDO	1.50	0.57	1.50	0.11	61%
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	0.61	0.69	3.94	0.19	16%
			PDO	0.72	0.35	4.98	0.13	3%
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	1.17	0.81	1.10	0.12	79%
			PDO	1.47	0.66	1.76	0.09	82%
All types	Signal control 2 to 6-lane crossroad	Rural or urban	FI	0.73	1.05	4.17	0.15	73%
			PDO	1.04	0.55	5.90	0.10	84%

FI = fatal and injury crashes; PDO = property damage only crashes.
*For use with the empirical Bayes procedure described in the *Highway Safety Manual.*
+Cumulative residual (CURE) plot ordinates for fitted values outside the 95% confidence intervals.

As shown in Table 8, the calibration factor ranged from 0.78 to 1.47 for the SPF groupings and from 0.68 to 1.50 for the individual SPFs. The calibration factor for FI crashes at stop-controlled ramp terminals (all types) was 1.20, indicating that the observed crashes were 20% higher than the HSM-predicted value. On the other hand, the calibration factor was 0.78 for signal-controlled ramp terminals (all types), which suggested that the observed crashes were 22% lower at these sites than that predicted by the HSM. In general, it appears that the HSM SPFs tended to overestimate crashes at signalized ramp terminals and underestimate crashes at stop-controlled terminals except for PDO crashes at signalized terminals (all types), for which the calibration factor was 1.00.

The CURE deviations were substantially high for all four SPF groupings (see Figure 3), ranging from 65% to 82%, including for PDO crashes at signal-controlled terminals, for which the calibration factor was 1.00.

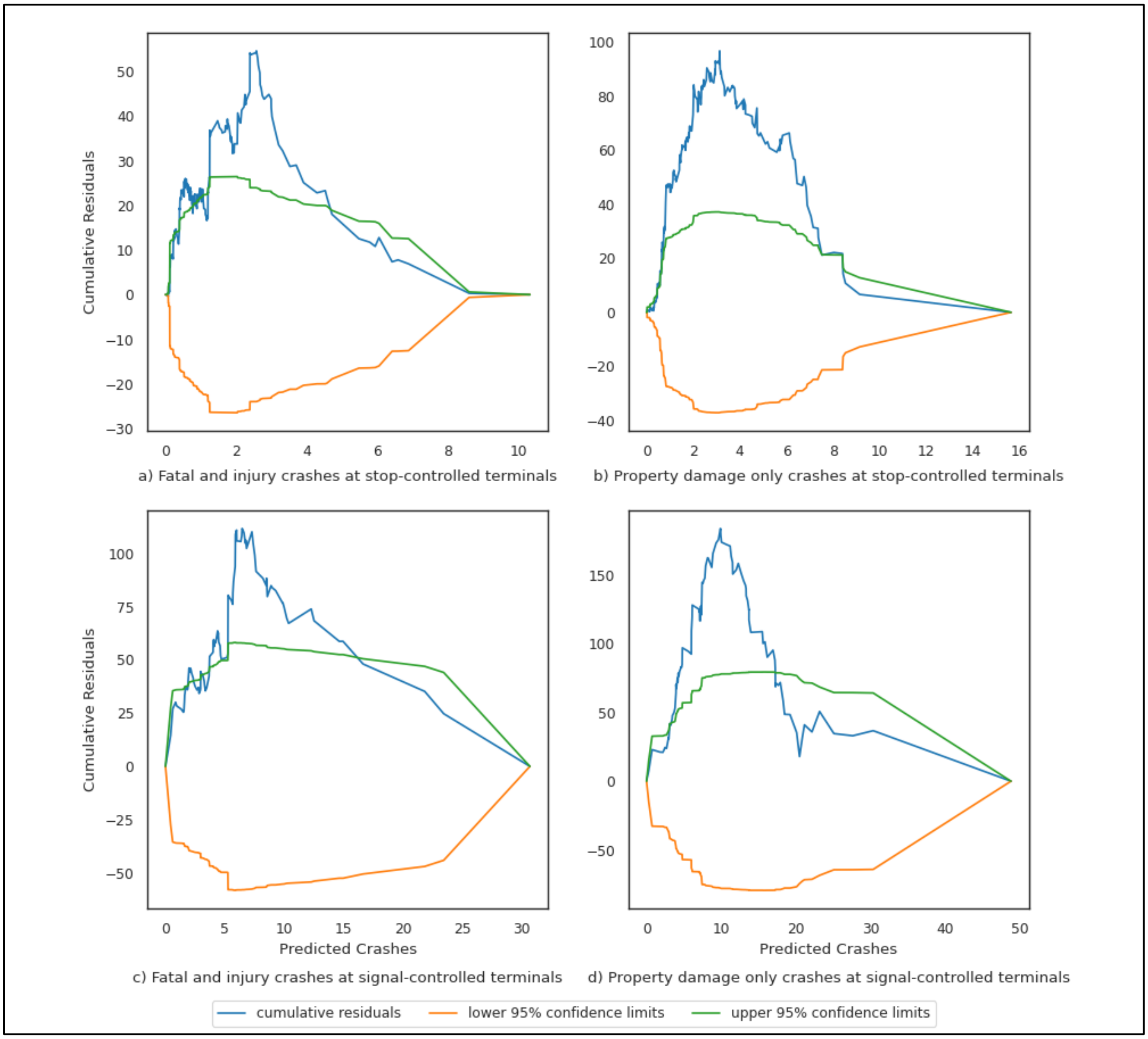

Figure 3. Cumulative Residual Plots for Fitted Values After Calibration Factors Applied

The CURE deviations suggested that the four individual SPFs calibrated better than the SPF groupings, even though only two met or nearly met the desired 5% maximum CURE deviation threshold. The coefficient of variation was fairly low (less than 20%) for all SPF and SPF groupings. The mean absolute deviations also seemed reasonable when compared to the observed crash data in Table 7. Similar trends were observed when all applicable CMFs (Table 8) and a maximum of only three CMFs (Table 9) were used.

The CURE deviations suggested that the application of a single calibration factor to the SPF or SPF groupings may not adequately calibrate the HSM ramp terminal SPFs to Virginia conditions. Therefore, calibration functions were developed in an attempt to improve the fit of the HSM models to Virginia data.

Calibration Function Results

Calibration functions were estimated for individual SPFs and SPF groupings. In each case, the Python Statsmodels package was used to fit a negative binomial model to the observed crash frequency (crashes per year) as a function of the HSM-predicted average crash frequency. Pertinent model output included estimates of the "*a*" and "*b*" calibration function parameters (see Equation 10) and the dispersion parameter. These values are shown in Tables 10 and 11. Also shown in the tables are relevant GOF measures including MAD and CURE deviation. It may be seen from the tables that the CURE deviations were substantially improved relative to the single calibration factor case.

It may also be seen from Figure 4 that using the two approaches to adjust the HSM SPF predictions resulted in nontrivial differences between the resulting average crash frequencies. Thus, for the dataset used in this study, it matters whether a calibration factor or calibration function is used to adjust the HSM SPF predictions to local conditions. In addition to providing a better fit of the data based on the CURE deviations, the nontrivial nature of the differences in the predicted crash frequencies provides further support for the calibration function (and the additional effort required to estimate it).

A review of the CURE deviations suggested that the calibrations using both all applicable CMFs and a maximum of three CMFs resulted in a good fit of the data. CURE plots for fitted values for the calibration using all applicable CMFs are shown in Figure 5. It is noted that CURE plots were derived for the crossroad and ramp AADTs and these also showed a good fit of the data with no obvious trends or "jumps" that would suggest significant bias or outliers.

The CURE deviations were comparable for all calibrated SPFs and SPF groupings except for the FI crash SPF for signalized ramp terminals (all types), where the CURE deviations were 3% and 11%, respectively, for when up to three CMFs versus all applicable CMFs were used (see Tables 10 and 11). For this SPF grouping, the mean absolute deviation and the dispersion parameters were comparable. Likewise, the estimated calibration parameters appeared comparable and suggested that the two sets of calibration parameters should, in practice, not produce significant differences in their predictions.

Table 10. Calibration Functions for Ramp Terminal Safety Performance Functions Determined Using All Applicable Crash Modification Factors

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Calibration Function		Dispersion Parameter	Goodness-of-Fit	
				a	***b***		**Mean Absolute Deviation**	**CURE Deviation**
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	0.96	0.79	0.23	0.82	6%
			PDO	1.27	0.67	0.48	1.47	1%
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	0.96	0.71	0.52	3.46	3%
			PDO	1.30	0.67	0.33	5.34	3%
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	0.93	0.65	0.63	1.07	3%
			PDO	1.29	0.61	0.51	1.66	8%
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	1.52	0.31	0.66	3.51	11%
			PDO	2.42	0.34	0.35	5.65	3%

FI = fatal and injury crashes; PDO = property damage only crashes.
Note: a, b are estimated calibration function parameters.

Table 11. Calibration Functions for Ramp Terminal Safety Performance Functions Based on Up to Three Applicable Crash Modification Factors

Terminal Type	Cross Section and Control Type	Area Type	Crash Severity	Calibration Function		Dispersion Parameter	Goodness-of-Fit	
				a	***b***		**Mean Absolute Deviation**	**CURE Deviation**
Four-leg terminal with diagonal ramps	One-way stop control 2-, 3-, 4-lane crossroad	Rural	FI	0.89	0.77	0.34	0.87	6%
			PDO	1.27	0.67	0.48	1.47	1%
Four-leg terminal with diagonal ramps	Signal control 4-lane crossroad	Rural or urban	FI	1.10	0.52	0.60	3.58	3%
			PDO	1.23	0.67	0.32	5.18	3%
All types	One-way stop control 2-, 3-, 4-lane crossroad	Rural or urban	FI	0.88	0.61	0.70	1.09	3%
			PDO	1.29	0.61	0.51	1.66	8%
All types	Signal control 2- to 6-lane crossroad	Rural or urban	FI	1.54	0.28	0.68	3.56	3%
			PDO	2.37	0.37	0.36	5.55	1%

FI = fatal and injury crashes; PDO = property damage only crashes.
Note: a, b are estimated calibration function parameters.

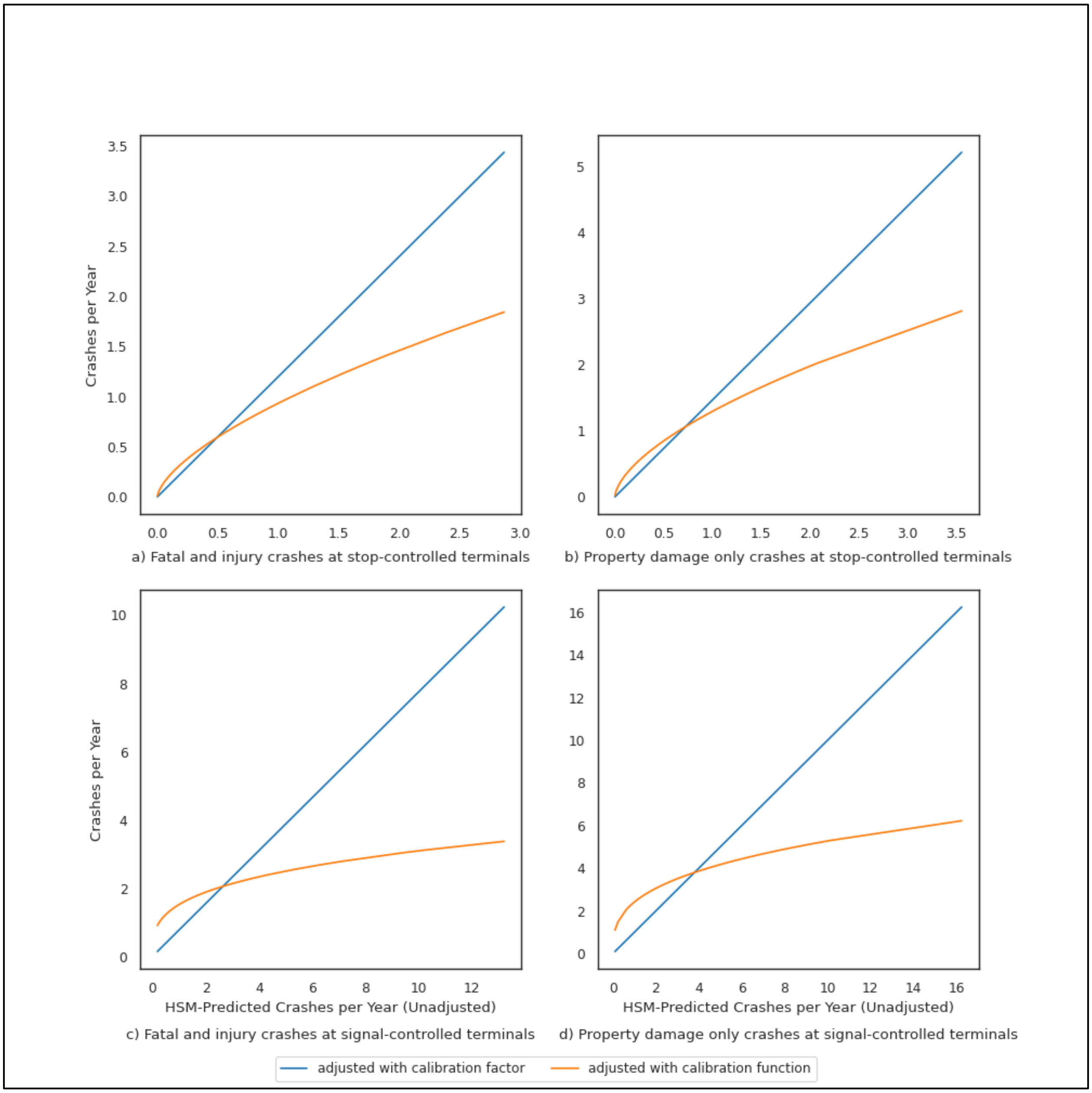

Figure 4. Predicted Crash Frequencies Using the Estimated Calibration Factors or Calibration Functions to Adjust the Uncalibrated Highway Safety Manual (HSM) Safety Performance Function Predictions

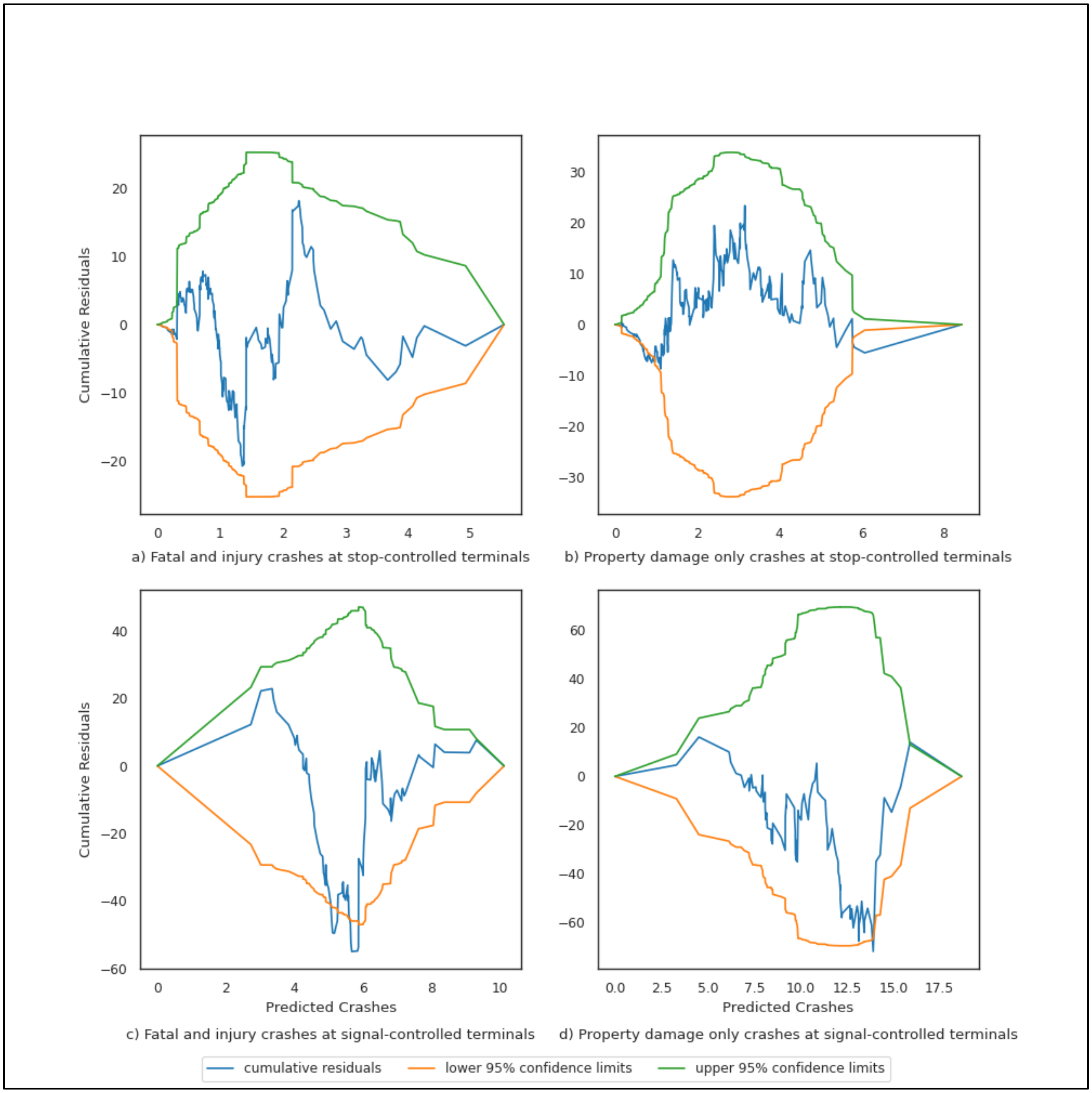

Figure 5. Cumulative Residual Plots for Fitted Values After Calibration Function Applied

This was confirmed in a small example using the two sets of parameter estimates to predict the average crash frequency over a range of up to 30 crashes per year (approximately the maximum expected crash frequency assuming base conditions, with crossroad and ramp AADTs set to the maximum allowable). The products of CMFs were set equal to 0.88 and 0.87, the average for this SPF grouping in the dataset (see Table 4) when a maximum of three CMFs or all applicable CMFs, respectively, were used. As expected, there were only marginal differences in the predictions.

To summarize, the CURE deviations suggest that both approaches—using a maximum of three CMFs versus using all applicable CMFs—calibrated well to Virginia data. Therefore, either set of calibration parameters produces acceptable results and may be recommended for adoption in Virginia.

Applying the Calibration Function

A central purpose of calibration is to facilitate application of the HSM predictive method. This section provides a summary of relevant steps needed to compute the predictive models shown in Equation 1 using the calibration function developed in this study. A more detailed description of the predictive modeling process is provided in Appendix C of the HSM. It is also noted that the HSM recommends that new values of the calibration factor be derived at least every 2 to 3 years. (By extension, since calibration functions are recommended for Virginia, the calibration functions in Step 7 should be updated every 2 to 3 years.)

1. *Determine applicable SPF*. This step identifies the ramp terminal SPF that is applicable to the study site. Information needed to identify the SPF is the type of configuration (see Figure 1), cross section (or number of lanes on the crossroad), area type, type of traffic control, and crash severity. With this information, the applicable SPF and relevant HSM tables containing the SPF coefficients can be determined from Table 1.

2. *Determine CMFs*. Table 2 summarizes the ramp terminal CMFs. This table may be used to identify CMFs that are applicable to the study site. Information needed to use the table includes the type of traffic control, area type, and crash severity. The table also includes the relevant HSM equations and coefficient tables.

3. *Assemble data*. In this step, the data needed to estimate the predictive model including AADT on the crossroad and ramps are collected. Data are also needed for site-specific geometric and operational conditions such as those listed in the section entitled "Task 3: Collection of Data" of this report. The specific data needed will depend on the CMFs identified in Step 2.

4. *Compute average crash frequency for base conditions*. Equation 2 is used together with the AADT data to determine the average crash frequency for base conditions. As noted in Step 1, the relevant SPF coefficients can be determined from Table 1.

5. *Compute CMFs*. The data assembled in Step 3 together with the CMF equations identified in Step 2 can be used to compute CMFs.

6. *Determine predicted average crash frequency*. The crash frequency determined for base conditions (Step 4) is multiplied by the CMFs (Step 5) to obtain the predicted average crash frequency, N_{HSM}.

7. *Identify calibration function parameters*. Depending on the number of CMFs used (a maximum of three or all applicable CMFs), Table 10 or 11 is used to select a set of calibration function parameters $\{a, b\}$ that are applicable for the study site.

8. *Compute the predicted average crash frequency, N_p.* The predicted average crash frequency for the study site is computed by using N_{HSM} (Step 6) together with the "*a*" and "*b*" parameter values (Step 7) in Equation 10.

CONCLUSIONS

- *Using a single calibration factor as a multiplier to adjust the HSM ramp terminal SPF predictions does not provide a good fit to Virginia data*. Between 65% and 82% of CURE plot ordinates for fitted values, based on the SPF groupings, were outside the 95% confidence interval. Individual SPFs calibrated better than the SPF groupings; however, only one out of four met the desired 5% CURE deviation threshold.

- *The calibration function developed in this study provides a superior fit of Virginia data to the HSM ramp terminal SPF predictions than the single calibration factor*. The percentage of CURE plot ordinates outside the 95% confidence interval ranged between 1% and 11% with five of eight calibrated SPFs and SPF groupings meeting the 5% CURE deviation threshold.

- *Limiting the number of CMFs to three resulted in a marginally better fit of the data compared to using all applicable CMFs.* CURE deviations ranged between 1% and 8% when the number of CMFs was limited to three and the CURE deviations were less than 5% for six of the eight SPF and SPF groupings that were calibrated.

RECOMMENDATIONS

1. *VDOT's Traffic Operations Division (TOD) should use the calibration function developed in this study with the ramp terminal SPFs in the HSM*. The use of Table 11 (based on three CMFs) is recommended because it reduces the workload (fewer CMFs to calculate) and provides at least a good a fit as using all applicable CMFs. Analysis at sites for which individual SPFs have been calibrated should use the corresponding calibrated parameter values. Analysis at all other ramp terminal sites should use parameter values calibrated for the applicable SPF grouping.

2. *VDOT's TOD should incorporate the calibration factors and application steps detailed in this report into the Traffic Operations and Safety Analysis Manual (TOSAM).* Inclusion of this information in TOSAM will ensure that VDOT staff and consultants apply these calibration factors consistently.

3. *VDOT's TOD should update the calibration functions on a regular basis*.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, within 6 months of the publication of this report, VDOT's TOD will encourage and promote the use of the calibration function developed in this study when the HSM ramp terminal SPFs are used.

With regard to Recommendation 2, within 1 year of the publication of this report, VDOT's TOD will prepare a step-by-step guidance document for inclusion in the next TOSAM update. TOSAM is updated as newer tools become available or when there are significant changes in the functionality of existing tools with the release of newer versions. Since TOSAM updates do not occur on a regular schedule, TOD will facilitate interim application of the calibration function by issuing a technical memorandum containing the proposed guidance. That document will be shared with district staff so that it can be applied to consultant work until this information is included in a TOSAM update.

With regard to Recommendation 3, within 1 month of the publication of this report, The Virginia Transportation Research Council (VTRC) will provide the code scripts developed to calibrate the HSM freeway ramp terminal SPFs in this study to VDOT's TOD. VTRC will also provide documentation of the software tools and computing resources used to run the analysis. TOD analysts will update the calibration functions following the instructions in the code scripts, as needed.

Benefits

Implementing these recommendations will facilitate the quantitative safety analysis of ramp terminal facilities and ensure better safety decisions. Calibration is important because safety conditions may differ significantly among jurisdictions as well as change over time. The application of uncalibrated or inappropriately calibrated SPFs may produce misleading results, compromise safety outcomes, and lead to inappropriate design decisions. For example, Figure 4 showed that differences of up to 10 crashes per year are probable when the prediction based on the calibration factor and the prediction based on the calibration function are compared. Even though Highway Safety Improvement Program (HSIP) applications are ultimately based on the ratio of monetized crash reduction benefits to expected out-of-pocket capital cost expenditures, it is not unusual for a difference of three crashes per year to affect whether an HSIP application is funded or not funded. Using the better prediction (as recommended by this study) will improve the selection of HSIP projects.

The three study recommendations all directly support these benefits. Specifically, the benefits of implementing Recommendation 1 would be higher accuracy of safety predictions. The benefits of implementing Recommendation 2 would be clear, concise information that VDOT divisions and consultants could immediately use to implement the calibration functions developed in this study. The benefits of implementing Recommendation 3 would be that calibration functions are kept up to date to ensure that the benefits of well-calibrated SPFs are maintained over time.

ACKNOWLEDGMENTS

The author thanks the following people who served on the technical review panel for this study: Stephen Read (Project Champion, Highway Safety Planning Manager, VDOT Traffic Operations Division), Ryan Krunz (Senior Highway Safety Engineer, VDOT Traffic Operations Division), John Miller (Associate Director, VTRC), and Jason Zhang (Assistant District Traffic Engineer, VDOT Richmond District).

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