

Intersection Safety Performance Function Calibration for Project Planning and Design

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Final Report VTRC 26-R34

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 26-R34		2. Government Accession No.:		3. Recipient's Catalog No.:	
4. Title and Subtitle: Intersection Safety Performance Function Calibration for Project Planning and Design				5. Report Date: March 2026	
				6. Performing Organization Code:	
7. Author(s): Justice Appiah, Ph.D., P.E.				8. Performing Organization Report No.: VTRC 26-R34	
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903				10. Work Unit No. (TRAIS):	
				11. Contract or Grant No.: 124329	
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation Federal Highway Administration 1221 E. Broad Street 400 North 8th Street, Room 750 Richmond, VA 23219 Richmond, VA 23219-4825				13. Type of Report and Period Covered: Final	
				14. Sponsoring Agency Code:	
15. Supplementary Notes: This is an SPR-B report.					
16. Abstract: <p>This study calibrated the predictive models for conventional intersections in the <i>Highway Safety Manual (HSM)</i> second edition draft to account for local conditions in Virginia. The calibration ensures that predictions made with the HSM safety performance functions accurately reflect the crash experience, driver population, and environmental characteristics of the state. Crash, traffic, and geometric data were collected for 1,326 intersections across Virginia, representing minor road stop-controlled, all-way stop-controlled, and signal-controlled configurations on rural two-lane, rural multilane, and urban or suburban arterial highways. The study followed HSM-recommended procedures to estimate calibration factors and dispersion parameters for the conventional intersection site-type safety performance functions in the HSM second edition draft.</p> <p>Constant calibration factors provided a good fit for total crashes, with 20 of 21 site types meeting HSM acceptance criteria, but they did not perform as well for fatal and injury crashes. Calibration functions offered a superior fit for those crash types, with 14 of 19 site types achieving percent cumulative residual deviations within 5%. It is recommended that the Virginia Department of Transportation Traffic Operations Division use the constant calibration factors in Table 11 for total crashes and the calibration functions in Table 12 for fatal and injury crashes and incorporate these results into the <i>Traffic Operations and Safety Analysis Manual</i> to ensure consistent statewide application.</p>					
17. Key Words: Highway Safety Manual, Safety Performance Function, Calibration, Conventional Intersection			18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report): Unclassified		20. Security Classif. (of this page): Unclassified		21. No. of Pages: 38	22. Price:

FINAL REPORT
INTERSECTION SAFETY PERFORMANCE FUNCTION CALIBRATION FOR
PROJECT PLANNING AND DESIGN

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

Charlottesville, Virginia

March 2026
VTRC 26-R34

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ABSTRACT

This study calibrated the predictive models for conventional intersections in the *Highway Safety Manual* (HSM) second edition draft to account for local conditions in Virginia. The calibration ensures that predictions made with the HSM safety performance functions accurately reflect the crash experience, driver population, and environmental characteristics of the state. Crash, traffic, and geometric data were collected for 1,326 intersections across Virginia, representing minor road stop-controlled, all-way stop-controlled, and signal-controlled configurations on rural two-lane, rural multilane, and urban or suburban arterial highways. The study followed HSM-recommended procedures to estimate calibration factors and dispersion parameters for the conventional intersection site-type safety performance functions in the HSM second edition draft.

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FINAL REPORT

INTERSECTION SAFETY PERFORMANCE FUNCTION CALIBRATION FOR PROJECT PLANNING AND DESIGN

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

INTRODUCTION

The *Highway Safety Manual* (HSM) provides a nationally recognized framework for quantitatively assessing the safety performance of transportation facilities (American Association of State Highway and Transportation Officials [AASHTO], 2010). It provides safety performance functions (SPFs), which are a predictive method to estimate the expected number of crashes on roadway segments and at intersections based on annual average daily traffic (AADT) volumes and key roadway geometric and traffic control features. The predictive method serves as the foundation for data-driven safety management, enabling transportation agencies to anticipate the safety performance of new facility designs, assess the safety performance of existing facilities, evaluate countermeasures, estimate the expected effectiveness of proposed improvements to an existing facility, and prioritize safety investments.

First published in 2010 by AASHTO, the HSM is currently being updated to incorporate new models and research completed since the manual's first edition. Planned modifications include SPFs for roundabouts and other intersection configurations and traffic control types not covered in the first edition (Ferguson et al., 2019; Torbic et al., 2021). The intersection SPFs planned for inclusion in the new HSM second edition (AASHTO, "unpublished data," estimated publication 2026), including those in the manual's current edition, were developed using national datasets and data from a subset of states, which may not fully reflect conditions in Virginia.

The Virginia Department of Transportation (VDOT) applies the HSM predictive methodology to support statewide safety analyses and project evaluations. Because the underlying national models may not reflect local road-user behavior, reporting practices, geometry, traffic mix, weather, or enforcement levels, the HSM recommends applying a calibration factor to the predicted crash frequency. Without appropriate calibration, the HSM models may over or underpredict crashes on Virginia highways, leading to potential inefficiencies in safety project prioritization and investment decisions.

PURPOSE AND SCOPE

The purpose of this study was to estimate calibration factors for key intersection types on the Virginia state highway network, thereby facilitating the application of HSM SPFs within the state. Specific objectives included the following:

- Evaluating the predictive performance of the HSM default SPFs relative to observed crash data in Virginia.
- Estimating calibration factors for rural two-lane, rural multilane, and urban or suburban signalized and unsignalized intersections.
- Providing recommended calibration factors for use in VDOT’s statewide safety management and project evaluation processes.

The scope was limited to SPFs for nonvulnerable road user-involved total crashes and fatal and injury crashes on the 34 conventional intersection site types defined in the HSM second edition for which sufficient data were available. Note that all references to the HSM second edition within this report refer specifically to the fall 2025 draft copy because the official edition has not yet been published. Also note that this study did not develop new SPFs; instead, the calibration process involved determining appropriate factors and functions that could be used to adjust the national SPFs to reflect crash experience in Virginia. VDOT engineers and planners can then use these factors and functions when evaluating potential intersection design and operations alternatives or when adding intersection safety treatments to make investment decisions.

METHODS

The researcher performed the following tasks to meet the project objectives:

1. Literature review.
2. Identification of priority SPFs and calibration sites.
3. Data collection.
4. Crash frequency prediction.
5. Derivation and assessment of calibration factors.

Task 1: Literature Review

The researcher identified literature on the latest developments regarding SPF calibration. The literature review helped identify the common methods and tools used to calibrate SPFs. The main sources for this information were AASHTO and Federal Highway Administration (FHWA) publications (AASHTO, 2010; Lyon et al., 2016; Srinivasan et al., 2013). Best practices and lessons learned from efforts in other states were also identified. The Transportation Research International Documentation database was used to search the literature.

Task 2: Priority Safety Performance Functions and Calibration Sites

Chapters 10 through 12 of the HSM first edition contain 41 SPFs for four intersection types on rural two-lane highways, rural multilane highways, and urban or suburban arterials (AASHTO, 2010). With the new HSM update, the scope of the SPFs in Chapters 10 through 12 was expanded to include more than 100 intersection types, such as various roundabout configurations, five-leg intersections, all-way stop control intersections, and three-leg turning intersections—intersections in which the through movement involves a turning maneuver. Because calibrating all the HSM intersection SPFs would be challenging because of both data

availability issues and the considerable effort required to assemble all relevant data, the researcher worked with the technical review panel to identify a subset of SPFs that are a priority to VDOT and focused the calibration effort on those SPFs. For example, anecdotal evidence suggested that not many one-way STOP or turn-priority three-approach STOP control sites exist in Virginia. In addition, several roundabout site types were unlikely to have the sample sizes and crash histories necessary for calibration because of the relatively recent history of these intersection types in the state. SPFs for these intersection types, as well as intersections that include a one-way street, could be investigated separately when it is determined that Virginia has sufficient sample numbers for calibration. Excluding roundabouts from consideration limited the calibration effort to the 34 conventional intersection site types summarized in Table 1.

Calibration Sites

The focus of this task was to determine if sufficient site-years of data exist to calibrate SPFs for the conventional intersection types and then select specific sites for calibration. For each intersection site type, a set of calibration sites was identified based on AADT and crash data availability, as well as sample size requirements specified in the HSM. In particular, the HSM recommends that a minimum of 30 to 50 sites is needed to calibrate SPFs for each site type. In addition, it recommends that the calibration dataset should include at least 100 crashes per year. These sample size requirements and data availability issues constrained the number of site types for which SPFs were ultimately calibrated. A list of more than 59,000 candidate intersections, characterized by the number of legs, control type (all-way stop, partial stop, or traffic signal), and geographic coordinates, was obtained from VDOT's Traffic Operations Division (TOD), which served as the basis for site selection. The first step in selecting calibration sites was to categorize intersections on this list into relevant HSM site types, which was done in five steps.

First, the unique link identifier associated with each intersection leg in VDOT's list was determined. This task was accomplished using *GeoPandas*—a Python module for geospatial analysis—by drawing a 30-foot buffer around the intersection locations and spatially joining them to a geodatabase of the VDOT network that contained link identifiers and other pertinent information, such as the start and end labels of the links.

Second, with the link identifier information, relevant link attribute data—such as rural-urban designation; number of lanes; VDOT facility type, including one way, two way, divided, or undivided; and speed limit—were obtained from the VDOT TOD's Oracle database, the Commonwealth of Virginia Traffic Engineering Data Operations Portal. No distinction is made between urban and suburban area types when applying the HSM predictive models (AASHTO, 2010). The link identifier information was also used to retrieve AADT data for the years 2022 through 2024 from the VDOT traffic monitoring system database using the link identifiers as the key.

Third, the links were classified into one of the HSM facility types—including rural two-way two-lane, rural multilane, and urban or suburban arterial—using the link attribute data retrieved from the Commonwealth of Virginia Traffic Engineering Data Operations Portal. Urban or suburban arterials were further classified into three categories: those with five or fewer lanes, those with six or more lanes, and whether they were one way or two way.

Table 1. Highway Safety Manual Conventional Intersection Site Types

Intersection Type	Intersections on Rural Two-Lane, Two-Way Roads	Intersections on Rural Multilane Highways	Intersections on Urban/Suburban Arterials where Both Roads Are One Way (1 x 1)	Intersections on Urban/Suburban Arterials where One Road Is One Way, and the Other Is Two Way (1 x 2)	Intersections on Urban/Suburban Arterials where Each Road Is Two Way and Has Five Lanes or Fewer (2 x 2)	Intersections between Two Two-Way Urban/Suburban Roads, at Least One of which Has Six or More Lanes (2 x 2)
3-Leg Minor STOP (3ST)	X	X	X	X	X	X
3-Leg Minor STOP High Speed (3ST-HS)					X	
3-Leg All-Way STOP (3AST)					X	
3-Leg STOP Turning (3STT)	X				X	
3-Leg Signalized (3SG)	X	X	X	X	X	X
3-Leg Signalized High Speed (3SG-HS)					X	
4-Leg Minor STOP (4ST)	X	X	X	X	X	X
4-Leg Minor STOP High Speed (4ST-HS)					X	
4-Leg All-Way STOP (4AST)	X				X	
4-Leg Signalized (4SG)	X	X	X	X	X	X
4-Leg Signalized High Speed (4SG-HS)					X	
5-Leg Signalized (5SG)					X	

Next, intersections were classified as rural two lane, rural multilane, or urban or suburban. Intersections were classified as rural two-way, two-lane intersections if all associated links belonged to this HSM facility type. They were classified as rural multilane intersections if at least one link was of a rural multilane HSM facility type, and none were urban or suburban. Those with only urban or suburban HSM facility type links were classified as urban or suburban intersections. Urban or suburban intersections were further classified into three subtypes: 1 x 1, 2 x 2, and 1 x 2 based on whether the associated links were exclusively one-way, exclusively two-way, or a combination of one-way and two-way links, respectively. The 2 x 2 subtype was reclassified as 2 x 2 with six or more lanes or 2 x 2 with five lanes or fewer, using the maximum number of lanes on all connected links. The 2 x 2 subtypes with five lanes or fewer were classified as high speed (50 miles per hour or higher) or not using the highest speed limit of all connected links.

Finally, intersections were identified as belonging to the different HSM site types using their classification from the preceding step and the control type and number of legs information from the VDOT TOD dataset. For example, a rural two-way, two-lane intersection from the preceding step would be classified as a 3SG site type intersection if it were signal controlled and had three legs. This dataset served as the sampling frame from which sites were selected for the study.

To the extent possible, applicable sites were randomly selected for inclusion in the calibration set for each site type and represent locations across the state. Only sites with AADT data were considered for selection. The list of candidate sites for each site type was shuffled once, and individual sites were considered for inclusion in the calibration set by going down the shuffled list and getting a cumulative count of crashes until the HSM-recommended minimum number of sites and crashes needed for calibration was met or the list was exhausted. While going down the shuffled list, sites were reviewed using Google Earth to verify that they were of the appropriate site type. Those with incorrect site type classifications (e.g., a four-leg intersection labeled three leg) were skipped.

Task 3: Data Collection

This task involved assembling detailed data needed to calibrate SPFs for the intersection site types. The data collection effort was limited to sites selected for inclusion in the calibration set as described previously. Three main types of data were collected: geometric and operational data, AADT data, and crash data. Table 2 summarizes the specific data elements.

Roadway AADT data were obtained from VDOT databases using the intersection link identifiers as previously described. Crash data were retrieved from the *VDOT Crash Analysis Tool* data portal. Relevant crashes were those that occurred within 250 feet of the intersection and did not involve pedestrians or bicycles. Data were collected for the years from 2022 to 2024.

Table 2. Calibration Data Needs by Site Type

Intersection Type	Intersections on Rural Two-Lane, Two-Way Roads	Intersections on Rural Multilane Highways	Intersections on Urban/Suburban Arterials where Both Roads Are One Way (1 x 1)	Intersections on Urban/Suburban Arterials where One Road Is One Way, and the Other Is Two Way (1 x 2)	Intersections on Urban/Suburban Arterials where Each Road Is Two Way and Has Five Lanes or Fewer (2 x 2)	Intersections between Two Two-Way Urban/Suburban Roads, at Least One of which Has Six or More Lanes (2 x 2)															
3-Leg Minor STOP (3ST)	1-6	1-6	1-4	1-4	1-5, 7	1-4															
3-Leg Minor STOP High Speed (3ST-HS)					1-5, 7																
3-Leg All-Way STOP (3AST)					1-4																
3-Leg STOP Turning (3STT)	1-4				1-3, 14																
3-Leg Signalized (3SG)	1-5	1-5	1-4, 9, 13	1-4, 9, 13	1-5, 7-10	1-4, 8-13															
3-Leg Signalized High Speed (3SG-HS)					1-5, 7																
4-Leg Minor STOP (4ST)	1-6	1-6	1-4	1-4	1-5, 7	1-4															
4-Leg Minor STOP High Speed (4ST-HS)					1-5, 7																
4-Leg All-Way STOP (4AST)	1-4				1-4																
4-Leg Signalized (4SG)	1-5	1-5	1-4, 9, 13	1-4, 9, 13	1-5, 7-10	1-4, 8-13															
4-Leg Signalized High Speed (4SG-HS)					1-5, 7																
5-Leg Signalized (5SG)					1-3																
<p>Key:</p> <table border="0"> <tr> <td>1. Number of legs</td> <td>6. Skew angle</td> <td>11. Right-turn channelization</td> </tr> <tr> <td>2. Type of traffic control</td> <td>7. Speed limit</td> <td>12. U-turn prohibition</td> </tr> <tr> <td>3. Annual average daily traffic</td> <td>8. Left-turn phasing</td> <td>13. Number of lanes (minor road and major road)</td> </tr> <tr> <td>4. Presence of lighting</td> <td>9. Right turn-on-red prohibition</td> <td>14. Horizontal curve (length and radius)</td> </tr> <tr> <td>5. Number of approaches with left- and right-turn lanes</td> <td>10. Use of red-light camera</td> <td></td> </tr> </table>							1. Number of legs	6. Skew angle	11. Right-turn channelization	2. Type of traffic control	7. Speed limit	12. U-turn prohibition	3. Annual average daily traffic	8. Left-turn phasing	13. Number of lanes (minor road and major road)	4. Presence of lighting	9. Right turn-on-red prohibition	14. Horizontal curve (length and radius)	5. Number of approaches with left- and right-turn lanes	10. Use of red-light camera	
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Table 2 shows that the data requirements also include several pieces of detailed geometric and operational data. Data elements such as the number of intersection legs, type of traffic control, and speed limit were obtained from VDOT sources. The remaining data elements—skew angle, presence of lighting, number of approaches with turn lanes, U-turn prohibition, and so on—were collected almost exclusively by reviewing satellite images of the calibration sites from Google Earth and Google Maps and using the Google Street View feature. Information regarding left-turn phasing was inferred by examining the intersection using Google Street View and looking at the positions and arrangements of the signal faces (shared or separate). For example, a shared four-section face with Circular Red, Circular Yellow, Circular Green, and left-turn Green Arrow was considered protected (Figure 1). General positions and arrangements of signal faces that were considered typical and used to infer data on left-turn phasing in this study are available in Figures 4D-6 through 4D-12 of the U.S. Department of Transportation’s (2009) *Manual on Uniform Traffic Control Devices* and in Figures 27 through 29 of the FHWA’s *Signalized Intersections Informational Guide* (Rodegerdts et al., 2004). Note that this approach is not definitive because Google Street View does not provide real-time signal displays, and some signals may change left-turn modes at different times of the day.

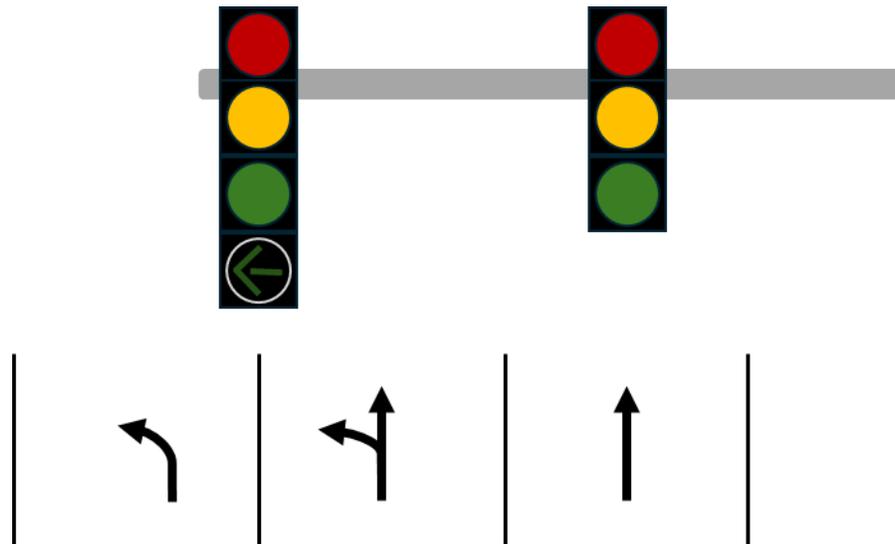


Figure 1. Possible Positions and Signal Face Assembly for Protected-Only Left-Turn Phasing

Data on red-light camera use were not collected because no readily available source was found at the level of detail needed. Therefore, no red-light use adjustment factors (AFs) were applied (i.e., assumed 1.0). This omission was considered reasonable because red-light cameras are not widely used at VDOT intersections.

Task 4: Crash Frequency Prediction

The data assembled in Task 3 were used to calculate a predicted average crash frequency for each calibration site using applicable HSM intersection SPFs. Six general forms of conventional intersection SPFs are available in the HSM. Table 3 shows the various equations and site types for which they are used. The sets of regression coefficient values used with these general forms vary based on the specific site type, crash type (single vehicle versus multivehicle), and crash severity (total or all severities, fatal and injury, property damage only,

and so on). A list of table numbers with the regression coefficient combinations is available in Table 13-22 of the HSM.

The crash frequency predictions produced by the HSM SPFs (N_{spf}) assume base conditions at the calibration sites (e.g., no skew, no lighting, and no turn lanes for rural STOP control intersections). For sites with conditions that differed from the base conditions, the HSM contains AFs that were applied to the SPF predictions to account for the actual site characteristics, as Equation 1 shows. Tables 14-18, 15-19, and 16-43 of the HSM summarize these AFs and the SPFs to which they apply.

$$N_{unc} = N_{spf} \times (AF_1 \times AF_2 \times \dots \times AF_m) \quad (\text{Equation 1})$$

Where:

N_{unc} = (uncalibrated) predicted average crash frequency (crashes/year).

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

$AF_1 \dots AF_m$ = a set of AFs to account for site-specific conditions.

Task 5: Derivation and Assessment of Calibration Values

In this task, calibration factors and relevant dispersion parameters necessary for the use of the Empirical Bayes procedure described in the HSM were estimated (AASHTO, 2010). The calibration factor, C , for each site type was determined by dividing the sum of observed crashes (across all applicable sites) by the sum of predicted crashes (for the same set of sites). Calibration factors were calculated for total crashes (all severities) and for fatal and injury crashes. The predicted crashes used here were those based on Equation 1. With the calibration factor known, the predicted average crash frequency (calibrated) at a site, N_{pred} , could be calculated using Equation 2.

$$N_{pred} = N_{unc} \times C \quad (\text{Equation 2})$$

Dispersion parameters were estimated for each site type by maximum likelihood methods assuming a negative binomial distribution of the errors. Specifically, a Python script was created to maximize the negative binomial likelihood function and, thus, determine the dispersion parameter values that maximized the likelihood of the calibration data (Appiah, 2023; Spiegelman et al., 2010).

The quality of the calibration was assessed using two goodness-of-fit measures recommended by the HSM, namely the coefficient of variation (CV) of the calibration factor and cumulative residual (CURE) plots. For each site type, CV was estimated as the ratio of the standard deviation to the estimated value of the calibration factor. CV is a measure of precision, with smaller values indicating a higher level of precision. The quality of the calibration was also assessed by evaluating CURE plots (observed minus predicted crashes) across fitted values (after applying the calibration factor).

Table 3. General Forms of Conventional Intersection Safety Performance Functions and the Site Types for which They Are Applicable

Intersection Type	Intersections on Rural Two-Lane, Two-Way Roads	Intersections on Rural Multilane Highways	Intersections on Urban/Suburban Arterials where Both Roads Are One Way (1 x 1)	Intersections on Urban/Suburban Arterials where One Road Is One Way, and the Other is Two Way (1 x 2)	Intersections on Urban/Suburban Arterials where Each Road Is Two Way and Has Five Lanes or Fewer (2 x 2)	Intersections between Two Two-Way Urban/Suburban Roads, at Least One of which Has Six or More Lanes (2 x 2)
3-Leg Minor STOP (3ST)	1	1	1	1	1	1
3-Leg Minor STOP High Speed (3ST-HS)					1	
3-Leg All-Way STOP (3AST)					2	
3-Leg STOP Turning (3STT)	2				2	
3-Leg Signalized (3SG)	1	1	1	1	1	1
3-Leg Signalized High Speed (3SG-HS)					1	
4-Leg Minor STOP (4ST)	1, 3	1	1	1	1	1
4-Leg Minor STOP High Speed (4ST-HS)					1	
4-Leg All-Way STOP (4AST)	3				1	
4-Leg Signalized (4SG)	1, 3	4	1	1	1	1
4-Leg Signalized High Speed (4SG-HS)					1	
5-Leg Signalized (5SG)					4, 5, 6	
<p>Key:</p> <p>1. $y = \exp(a + b \ln(X_1) + c \ln(X_2))$ 2. $y = \exp(a + b \ln(X_3))$ 3. $y = \exp(a + b \ln(X_4))$ 4. $y = \exp(a + b \ln(X_5))$ 5. $y = \exp(a + b \ln(X_1) + c \ln(X_2) + d \ln(X_6))$ 6. $y = \exp(a + b \ln(X_1) + c \ln(X_7))$</p> <p>$X_1$: AADT for major road approaches X_2: AADT for minor road approaches X_3: Total entering volume at a three-leg intersection, veh/day X_4: Total entering volume at a four-leg intersection, veh/day</p> <p>X_5: Sum of major road and minor road AADTs X_6: AADT for the 5th road leg at a five-leg intersection X_7: Combined AADT for minor road and the 5th road leg at a five-leg intersection a, b, c, d: Regression coefficients (see draft HSM, Table 13-22 for coefficients)</p>						

AADT = annual average daily traffic; HSM = *Highway Safety Manual*; veh = vehicles.

According to the HSM second edition, the estimated constant (or single) calibration factor can be considered reliable if either of the two following conditions is met (AASHTO, “unpublished data”):

1. Five percent or less of CURE plot ordinates exceed the 2 standard deviation confidence limits.
2. CV is less than 0.15.

When neither condition is met, HSM-recommended remedies include the following:

- Adding additional sites to the calibration set and redoing the calibration, if possible.
- Combining site types, where appropriate, and developing a common calibration factor.
- Developing a calibration function.
- Calibrating another SPF, if one is available.
- Developing a jurisdiction-specific SPF.

For this study, most site types satisfied these criteria for total crashes. However, several site types failed the criteria for fatal and injury crashes. Because of the considerable expense (time and effort) needed to collect data with sufficient fatal and injury crashes to meet the HSM-recommended data requirements, calibration functions were developed when constant calibration factors provided a poor fit as defined by the previous criteria.

Equation 3 shows the general form of the calibration function adopted for this study.

$$N_{pred} = a \times (N_{unc})^b \quad \text{(Equation 3)}$$

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

This form of the calibration function 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 the 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

Literature Review

The HSM presents predictive models to estimate expected crash frequencies for roadway segments and intersections, given traffic exposure (e.g., major or minor AADT at intersections), base conditions, and AFs to adjust for site-specific attributes (such as lane width, turning lanes, and skew angle) that might differ from the base conditions (AASHTO, 2010). Because the underlying national models may not reflect local road-user behavior, reporting practices,

geometry, traffic mix, weather, or enforcement levels, the HSM recommends applying a calibration factor (C) to the predicted crash frequency as shown in Equation 2.

The goal of calibration is to align the prediction model with the local crash experience of a jurisdiction (state, region, or agency). The HSM provides a systematic process for calibration, namely: define facility types, gather observed crash and exposure data, compute predicted frequency from HSM SPFs, derive the ratio of observed to predicted crashes, assess sample size adequacy, perform outlier screening, and evaluate whether calibration alone is adequate or a state-specific SPF is required (AASHTO, 2010).

A recent National Cooperative Highway Research Program synthesis surveyed state departments of transportation (DOTs) and found that 65% of the responding DOTs develop their own SPFs, and among those applying HSM SPFs, 67% apply calibration factors (Gayah et al., 2024). The study also noted several state DOT calibration and state-specific SPF development efforts, including the following:

- A Massachusetts study found calibration factors for three- and four-leg signalized intersections significantly greater than 1.0, meaning crash frequencies exceeded HSM predictions (Xie and Chen, 2016).
- In Illinois, calibration factors for intersections ranged widely—for example, 0.24 for three-leg, stop-controlled intersections on rural two-way, two-lane roads from 2006 to 2008; 3.22 for four-leg signalized intersections on urban or suburban arterials during the same period (Illinois DOT, 2014).
- Kansas intersection calibration efforts found the 4-leg rural, stop-controlled intersections calibration factor of 0.91 for total crashes in one study and other types around 0.51 to 1.17, depending on leg or area type (Dissanayake and Aziz, 2016; Dissanayake and Karmacharya, 2020).
- The review also highlights that states with significant geographic or traffic heterogeneity (for example, mountainous versus flat terrain and variable reporting rates) often find that calibration factors differ by region within the state.

Some other key findings from the National Cooperative Highway Research Program synthesis included the following (Gayah et al., 2024):

- Sample size is critical. The HSM suggests a minimum of 100 crashes per facility type or 30 to 50 sites for intersections, but many state studies cite fewer.
- Calibration factors vary by state, facility type, severity (total versus fatal and injury), area type (urban versus rural), terrain and climate, and data quality.
- In some jurisdictions, the calibration factors were very large (> 2.0) or very small (< 0.5), suggesting that the national SPFs may not fit well, and a state-specific SPF may be needed.
- Many agencies combine calibration with state-specific SPF development when local conditions diverge significantly from the national sample underpinning the HSM SPFs.

Priority Safety Performance Functions and Calibration Sites

The new HSM update includes more than 100 SPFs for a wide range of intersection types. Given data limitations and the effort required to calibrate SPFs, this study prioritized calibrating SPFs for the 34 conventional intersection site types included in the HSM.

More than 59,000 candidate intersections obtained from VDOT were evaluated using geospatial analysis tools to identify, classify, and select suitable calibration sites. Intersections were classified by facility type, control, and geometry into relevant HSM site types. The resulting dataset, summarized in Table 4, served as the sampling frame from which sites were selected for calibration.

Site selection followed HSM recommendations for sample size and crash history. Each intersection selected for inclusion in the calibration set was verified for accurate HSM site type assignment or classification using Google Earth imagery. Several intersections in the sampling frame were discarded during the manual review process because of misclassification due to data quality issues (e.g., incorrect number of legs, lanes, and so on). For example, only four of the 109 urban 2 x 2 five-leg signalized intersections were usable. For rural two-way, two-lane intersections, the HSM-recommended threshold of 100 crashes per year was reached only after reviewing more than 200 intersections. A total of 1,365 sites were selected through the review process. However, 39 of these sites were later discarded because AADTs were outside the limits for which SPFs were applicable, as defined in the HSM. The final dataset used for calibration included 1,326 intersections across Virginia (Figure 2). Table 5 summarizes the number and crash history for intersections of each HSM site type in the dataset available for calibration.

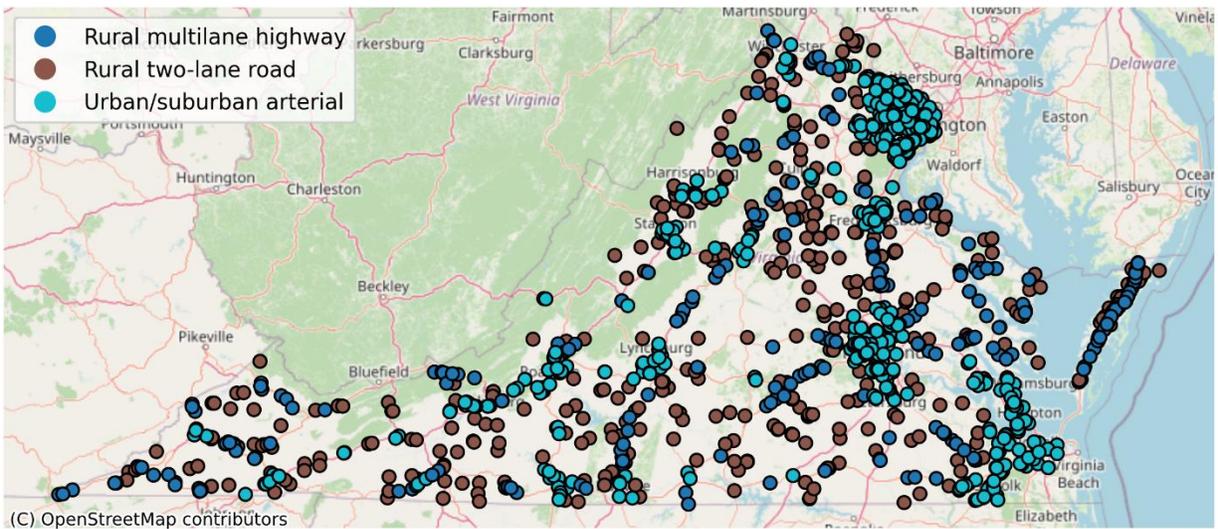


Figure 2. Map Showing Locations of Study Intersections

Table 4. Number of Intersections of Each Site Type Assembled for Possible Inclusion in Calibration Dataset

Site Type	No. of Sites	Crashes per Year	
		All Crash Severities	Fatal and Injury Crashes
<i>Intersections on rural two-lane, two-way roads</i>			
3-Leg Signalized (3SG)	30	44.7	10.3
3-Leg Minor STOP (3ST)	3,862	1761.7	546.0
3-Leg STOP Turning (3STT)	0		
4-Leg All-Way STOP (4AST)	1	3.7	1.7
4-Leg Signalized (4SG)	58	123.7	37.7
4-Leg Minor STOP (4ST)	902	755.7	291.0
<i>Intersections on rural multilane highways</i>			
3-Leg Signalized (3SG)	65	142.7	51.0
3-Leg Minor STOP (3ST)	548	466.3	158.7
4-Leg Signalized (4SG)	125	399.7	128.7
4-Leg Minor STOP (4ST)	410	535.7	220.3
<i>Intersections on urban or suburban arterials where both roads are one way (1 x 1)</i>			
3-Leg Signalized (3SG)	0		
3-Leg Minor STOP (3ST)	0		
4-Leg Signalized (4SG)	1	2.3	0.3
4-Leg Minor STOP (4ST)	0	0.0	0.0
<i>Intersections on urban or suburban arterials where one road is one way, and the other is two way (1 x 2)</i>			
3-Leg Signalized (3SG)	4	8.3	2.0
3-Leg Minor STOP (3ST)	4	2.0	0.7
4-Leg Signalized (4SG)	26	80.0	26.3
4-Leg Minor STOP (4ST)	1	0.7	0.0
<i>Intersections on urban or suburban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>			
3-Leg All-Way STOP (3AST)	0		
3-Leg Signalized (3SG)	426	1,344.3	426.0
3-Leg Signalized High Speed (3SG-HS)	93	333.3	117.0
3-Leg Minor STOP (3ST)	3,211	2,466.0	673.0
3-Leg STOP Turning (3STT)	0		
3-Leg Minor STOP High Speed (3ST-HS)	250	349.3	128.0
4-Leg All-Way STOP (4AST)	14	66.0	13.3
4-Leg Signalized (4SG)	983	3,954.7	1,324.3
4-Leg Signalized High Speed (4SG-HS)	247	1,361.0	473.7
4-Leg Minor STOP (4ST)	1,343	1,592.0	457.3
4-Leg Minor STOP High Speed (4ST-HS)	155	304.3	113.3
5-Leg Signalized (5SG)	109	466.3	158.3
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>			
3-Leg Signalized (3SG)	181	1,066.3	325.3
3-Leg Minor STOP (3ST)	116	272.0	73.0
4-Leg Signalized (4SG)	563	4,767.0	1,644.0
4-Leg Minor STOP (4ST)	128	360.7	103.0

Table 5. Intersections Used for Calibration and Their Crash Histories

Site Type	No. of Sites	Total Crashes per Year					Fatal and Injury Crashes per Year				
		Mean	Std	Min	Max	Sum	Mean	Std	Min	Max	Sum
<i>Intersections on rural two-lane, two-way roads</i>											
3-Leg Signalized (3SG)	28	1.2	1.0	0.0	4.0	33.0	0.2	0.4	0.0	1.0	6.7
3-Leg Minor STOP (3ST)	216	0.4	0.4	0.0	2.3	90.0	0.1	0.2	0.0	1.0	25.0
3-Leg STOP Turning (3STT)	0										
4-Leg All-Way STOP (4AST)	1	3.7		3.7	3.7	3.7	1.7		1.7	1.7	1.7
4-Leg Signalized (4SG)	54	1.7	1.5	0.0	7.3	90.3	0.5	0.6	0.0	2.3	24.3
4-Leg Minor STOP (4ST)	113	0.8	1.0	0.0	7.3	91.7	0.3	0.5	0.0	2.3	37.3
<i>Intersections on rural multilane highways</i>											
3-Leg Signalized (3SG)	26	2.7	2.1	0.3	8.3	71.3	1.0	1.0	0.0	3.7	26.0
3-Leg Minor STOP (3ST)	136	0.7	0.8	0.0	6.0	99.0	0.3	0.4	0.0	2.0	35.0
4-Leg Signalized (4SG)	23	2.8	1.6	0.7	6.3	65.3	0.9	0.6	0.0	2.0	21.0
4-Leg Minor STOP (4ST)	60	1.7	1.7	0.0	9.3	103.7	0.8	0.9	0.0	5.7	45.3
<i>Intersections on urban or suburban arterials where both roads are one way (1 x 1)</i>											
3-Leg Signalized (3SG)	0										
3-Leg Minor STOP (3ST)	0										
4-Leg Signalized (4SG)	7	2.1	1.3	0.7	4.0	15.0	0.8	0.7	0.0	1.7	5.3
4-Leg Minor STOP (4ST)	0										
<i>Intersections on urban or suburban arterials where one road is one way, and the other is two way (1 x 2)</i>											
3-Leg Signalized (3SG)	0										
3-Leg Minor STOP (3ST)	0										
4-Leg Signalized (4SG)	9	4.1	2.6	0.3	8.3	37.0	1.2	1.0	0.3	3.3	10.7
4-Leg Minor STOP (4ST)	0										
<i>Intersections on urban or suburban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>											
3-Leg All-Way STOP (3AST)	0										
3-Leg Signalized (3SG)	41	2.6	2.4	0.0	12.7	105.0	0.9	1.0	0.0	4.0	36.3
3-Leg Signalized High Speed (3SG-HS)	34	3.4	2.7	0.3	9.7	114.3	1.4	1.6	0.0	6.3	46.7

Site Type	No. of Sites	Total Crashes per Year					Fatal and Injury Crashes per Year				
		Mean	Std	Min	Max	Sum	Mean	Std	Min	Max	Sum
3-Leg Minor STOP (3ST)	160	0.6	0.7	0.0	3.3	102.7	0.2	0.3	0.0	1.3	30.0
3-Leg STOP Turning (3STT)	0										
3-Leg Minor STOP High Speed (3ST-HS)	85	1.2	1.2	0.0	7.7	103.7	0.4	0.5	0.0	3.3	37.3
4-Leg All-Way STOP (4AST)	12	4.9	3.8	1.3	14.0	59.3	1.0	1.0	0.0	2.7	12.0
4-Leg Signalized (4SG)	30	4.9	5.0	1.0	27.0	148.3	1.8	3.6	0.0	20.0	55.0
4-Leg Signalized High Speed (4SG-HS)	30	6.1	3.2	1.0	13.7	183.0	2.1	1.9	0.0	8.0	61.7
4-Leg Minor STOP (4ST)	80	1.3	1.4	0.0	6.7	107.0	0.4	0.6	0.0	4.0	30.0
4-Leg Minor STOP High Speed (4ST-HS)	60	2.0	1.3	0.0	5.7	119.0	0.8	0.7	0.0	3.7	46.0
5-Leg Signalized (5SG)	4	3.9	2.4	1.7	7.0	15.7	1.3	1.2	0.0	2.7	5.3
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>											
3-Leg Signalized (3SG)	29	5.4	4.1	0.3	16.7	158.0	1.7	1.5	0.0	8.0	48.0
3-Leg Minor STOP (3ST)	29	3.1	2.5	0.3	11.3	89.7	0.8	0.8	0.0	3.3	24.0
4-Leg Signalized (4SG)	33	10.4	7.2	0.3	33.0	342.7	4.3	5.3	0.3	27.0	141.0
4-Leg Minor STOP (4ST)	26	3.0	2.3	0.3	8.3	77.7	0.9	0.9	0.0	3.7	22.7

Max = maximum; Min = minimum; Std = standard deviation.

Nine of the 34 site types did not have intersections with usable data, and most of these site types were intersections with one-way roads. Also, only a few five-leg intersections (four total) and All-Way stop intersections (13 total, including one on a rural two-way, two-lane road and 12 on two-way urban arterials) were available. Intersections with one-way roads were combined, and a common calibration factor was explored. Likewise, All-Way stop intersections were combined. Several intersections met, or nearly met, the 100-crashes-per-year threshold when considering total crashes. However, this threshold was not met when considering fatal and injury crashes. This scenario is likely because total crashes were used as the criteria when selecting sites for inclusion in the calibration dataset. Fatal and injury crashes were not used because the number of candidate sites that would have had to be reviewed to meet a 100-crashes-per-year threshold would have been too labor intensive to be practical. For example, 25 fatal and injury crashes per year were found for rural two-lane intersections after reviewing more than 200 sites. Nevertheless, because fatal and injury crash data tend to be more reliable than property damage-only crashes, calibration factors for these crash types were explored.

Data Summary

SPF calibration is a data-intensive process. Geometric and operational data, AADT, and crash data were assembled for calibration. Geometric and operational data—including intersection skew, number of approaches with turn lanes, right-turn channelization, and use of right turn-on-red signals—were obtained primarily by reviewing Google Earth images and Google Street View panoramic photographs of candidate sites. AADT and crash data were obtained from VDOT sources.

Table 6 summarizes the AADT data used to calibrate SPFs, and Table 5 shows the crash data. As expected, AADTs were generally higher for urban intersections. More crashes, both total and fatal and injury, occurred per site-year at the urban intersections, which was not surprising given the generally higher traffic volumes at these intersections.

Several data elements were collected on geometric and operational characteristics at the calibration sites, which were used to calculate AFs for use with SPFs. HSM SPFs for conventional intersections on rural multilane highways use different AF values for total crashes (all severities) and fatal and injury crashes. In contrast, AFs for intersections on the other two roadway types are not distinguished by severity. Table 7 summarizes the composite estimates of these AFs, obtained by multiplying all applicable AFs at a given site. The composite estimates quantify the overall adjustments needed to account for geometric and operational conditions at the calibration sites that differed from the base conditions for which HSM SPFs were developed. The values in Table 7 (see “mean” columns) suggest that the base SPF models overpredict crashes on average at the calibration sites. AF would be 1.0 if no over or underprediction occurred. These results highlight the need to adjust for site-specific conditions when using SPFs contained in the HSM.

Table 6. Summary of Annual Average Traffic Volume Data

Site Type	No. of Sites	Major-Road Traffic (veh/day)			Minor-Road Traffic (veh/day)		
		Mean	Min	Max	Mean	Min	Max
<i>Intersections on rural two-lane, two-way roads</i>							
3-Leg Signalized (3SG)	28	9,355	2,929	23,467	3,478	189	9,280
3-Leg Minor STOP (3ST)	216	2,439	142	13,710	435	13	2,904
4-Leg Signalized (4SG)	54	7,560	1,855	14,474	3,404	473	7,881
4-Leg Minor STOP (4ST)	113	2,509	140	7,669	655	40	2,431
<i>Intersections on rural multilane highways</i>							
3-Leg Signalized (3SG)	26	14,678	2,327	30,092	4,482	57	10,976
3-Leg Minor STOP (3ST)	136	12,150	1,615	28,925	630	10	5,513
4-Leg Signalized (4SG)	23	15,828	3,684	22,047	2,679	757	7,987
4-Leg Minor STOP (4ST)	60	12,639	3,785	30,092	1,153	15	4,205
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>							
3-Leg Signalized (3SG)	41	16,747	6,802	39,635	6,128	22	16,254
3-Leg Signalized High Speed (3SG-HS)	34	17,386	6,060	43,483	4,795	1,184	13,557
3-Leg Minor STOP (3ST)	160	7,181	254	32,272	725	11	6,557
3-Leg Minor STOP High Speed (3ST-HS)	85	15,297	1,371	41,159	1,082	15	4,920
4-Leg Signalized (4SG)	30	20,652	8,410	47,864	8,872	1,584	26,789
4-Leg Signalized High Speed (4SG-HS)	30	21,995	4,939	48,307	6,035	382	15,722
4-Leg Minor STOP (4ST)	80	8,902	470	38,423	1,153	68	5,219
4-Leg Minor STOP High Speed (4ST-HS)	60	17,812	2,096	41,159	1,097	30	4,356
5-Leg Signalized (5SG)	4	13,335	8,180	22,076	10,476	6,088	17,906
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>							
3-Leg Signalized (3SG)	29	43,008	13,780	82,229	7,960	623	21,835
3-Leg Minor STOP (3ST)	29	44,968	21,249	64,956	1,384	41	5,728
4-Leg Signalized (4SG)	33	39,822	20,026	72,593	10,593	1,452	30,040
4-Leg Minor STOP (4ST)	26	36,116	13,573	54,093	1,126	124	4,182
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>							

Site Type	No. of Sites	Major-Road Traffic (veh/day)			Minor-Road Traffic (veh/day)		
		Mean	Min	Max	Mean	Min	Max
4-Leg Signalized (4SG)	16	4,437	1,644	9,438	6,826	827	29,786
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>							
4-Leg All-Way STOP (4AST)	13	8,084	4,530	117,68	5,104	738	8,609

Max = maximum; Min = minimum; veh = vehicles.

Table 7. Composite Adjustment Factors for Crash Predictions

Site Type	No. of Sites	II(AF) All Crash Severities			II(AF) Fatal and Injury Crashes		
		Mean	Min	Max	Mean	Min	Max
<i>Intersections on rural two-lane, two-way roads</i>							
3-Leg Signalized (3SG)	28	0.69	0.61	1.00	0.69	0.61	1.00
3-Leg Minor STOP (3ST)	216	1.03	0.48	1.35	1.03	0.48	1.35
4-Leg Signalized (4SG)	54	0.66	0.34	0.92	0.66	0.34	0.92
4-Leg Minor STOP (4ST)	113	1.00	0.43	1.35	1.00	0.43	1.35
<i>Intersections on rural multilane highways</i>							
3-Leg Signalized (3SG)	26	0.71	0.61	1.00	0.87	0.83	1.00
3-Leg Minor STOP (3ST)	136	0.73	0.43	1.51	0.68	0.35	1.68
4-Leg Signalized (4SG)	23	0.55	0.36	0.90	0.84	0.69	1.00
4-Leg Minor STOP (4ST)	60	0.57	0.34	1.59	0.48	0.25	1.73
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>							
3-Leg Signalized (3SG)	41	0.75	0.64	0.94	0.75	0.64	0.94
3-Leg Signalized High Speed (3SG-HS)	34	0.79	0.73	0.93	0.79	0.73	0.93
3-Leg Minor STOP (3ST)	160	0.89	0.52	1.00	0.89	0.52	1.00
3-Leg Minor STOP High Speed (3ST-HS)	85	0.72	0.51	1.00	0.72	0.51	1.00
4-Leg Signalized (4SG)	30	0.55	0.40	0.87	0.55	0.40	0.87
4-Leg Signalized High Speed (4SG-HS)	30	0.60	0.51	0.75	0.60	0.51	0.75
4-Leg Minor STOP (4ST)	80	0.74	0.36	1.00	0.74	0.36	1.00
4-Leg Minor STOP High Speed (4ST-HS)	60	0.52	0.36	1.00	0.52	0.36	1.00
5-Leg Signalized (5SG)	4	1.00	1.00	1.00	1.00	1.00	1.00

Site Type	No. of Sites	II(AF) All Crash Severities			II(AF) Fatal and Injury Crashes		
		Mean	Min	Max	Mean	Min	Max
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>							
3-Leg Signalized (3SG)	29	0.83	0.62	1.16	0.83	0.62	1.16
3-Leg Minor STOP (3ST)	29	0.93	0.91	1.00	0.93	0.91	1.00
4-Leg Signalized (4SG)	33	1.88	1.36	2.60	1.88	1.36	2.60
4-Leg Minor STOP (4ST)	26	0.94	0.91	1.00	0.94	0.91	1.00
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>							
4-Leg Signalized (4SG)	16	1.15	0.91	2.19	1.15	0.91	2.19
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>							
4-Leg All-Way STOP (4AST)	13	0.91	0.89	1.00	0.91	0.89	1.00

Max = maximum; Min = minimum; II(AF) = product of all applicable adjustment factors.

Calibration Results

Predicted Crashes

The first step was to calculate 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 3). This predicted crash frequency was then multiplied by applicable AFs to account for site-specific geometric and operational conditions. Table 8 shows the predicted crash frequencies, including applicable AFs.

The predicted crash frequency was highest for four-leg signalized intersections on urban arterials with six or more lanes at 18.5 crashes per site-year for all crash severities combined (1,836 3-year total) compared with an observed frequency of 10.4 crashes per site-year (1,028 3-year total) at these intersections.

A calibration factor was calculated for each SPF by dividing the sum of observed crashes at all calibration sites, for each site type, by the sum of the SPF-predicted crashes at the same set of sites. Table 9 summarizes the results, including the recalibrated dispersion parameter and other goodness-of-fit measures. All calculations were performed following HSM procedures. Results for site types for which CV was no more than 0.15 or no more than 5% of CURE ordinates fell outside the 2 standard deviation confidence band are highlighted in gray. Figure 3 shows example CURE plots demonstrating good fit for total crash data at selected site types. The Appendix summarizes the CURE plots for all site types. According to the HSM, calibration is considered adequate if any of these criteria are met. Nearly all site types satisfied at least one of these criteria for total crashes except rural multilane 4STs, 5SGs on 2 x 2 urban arterials, and four-leg All-Way stops. The latter two had low sample sizes, so these results were expected. The 4ST types on rural multilane highways barely missed the CV criterion ($CV = 0.16$).

For fatal and injury crashes, only 10 site types met at least one of the two HSM criteria. This scenario is likely because none of these site types contained the 100 crashes per year recommended by the HSM. Collecting enough data to meet this threshold for the number of site types that would need to be recalibrated would be too labor intensive to be practical. Consequently, the use of calibration functions was explored. Table 10 summarizes the results. The focus was on those sites that did not satisfy the HSM acceptance criteria when using a constant calibration factor. Table 10 shows that calibration functions offered an improved fit, with 14 of 19 site types achieving percent CURE deviations within 5%.

Table 8. Safety Performance Function Predicted Crashes^a

Site Type	No. of Sites	Σ(Observed)		Σ(Predicted)	
		All Crash Severities	Fatal and Injury Crashes	All Crash Severities	Fatal and Injury Crashes
<i>Intersections on rural two-lane, two-way roads</i>					
3-Leg Signalized (3SG)	28	99	20	126	47
3-Leg Minor STOP (3ST)	216	270	75	225	73
4-Leg Signalized (4SG)	54	271	73	289	105
4-Leg Minor STOP (4ST)	113	275	112	304	127
<i>Intersections on rural multilane highways</i>					
3-Leg Signalized (3SG)	26	214	78	184	51
3-Leg Minor STOP (3ST)	136	297	105	213	79
4-Leg Signalized (4SG)	23	196	63	200	79
4-Leg Minor STOP (4ST)	60	311	136	166	61
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>					
3-Leg Signalized (3SG)	41	315	109	241	83
3-Leg Signalized High Speed (3SG-HS)	34	343	140	350	122
3-Leg Minor STOP (3ST)	160	308	90	205	79
3-Leg Minor STOP High Speed (3ST-HS)	85	311	112	352	116
4-Leg Signalized (4SG)	30	445	165	281	92
4-Leg Signalized High Speed (4SG-HS)	30	549	185	718	233
4-Leg Minor STOP (4ST)	80	321	90	218	76
4-Leg Minor STOP High Speed (4ST-HS)	60	357	138	376	154
5-Leg Signalized (5SG)	4	47	16	70	18
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>					
3-Leg Signalized (3SG)	29	474	144	483	249
3-Leg Minor STOP (3ST)	29	269	72	255	118
4-Leg Signalized (4SG)	33	1,028	423	1,836	961
4-Leg Minor STOP (4ST)	26	233	68	165	79
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>					
4-Leg Signalized (4SG)	16	156	48	101	26
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>					
4-Leg All-Way STOP (4AST)	13	189	41	62	18

^a Crash data shown are a sum for all sites across all 3 years from 2022 to 2024.

Table 9. Calibration Factor Results

Site Type	No. of Sites	All Crash Severities				Fatal and Injury Crashes			
		Calibration Factor	Dispersion Parameter	CV	CURE Deviation ^a	Calibration Factor	Dispersion Parameter	CV	CURE Deviation ^a
<i>Intersections on rural two-lane, two-way roads</i>									
3-Leg Signalized (3SG)	28	0.79	0.21	0.15	0.04	0.43	0.89	0.39	0.04
3-Leg Minor STOP (3ST)	216	1.20	0.01	0.06	0.91	1.03	0.01	0.12	0.71
4-Leg Signalized (4SG)	54	0.94	0.43	0.13	0.06	0.70	0.78	0.23	0.02
4-Leg Minor STOP (4ST)	113	0.91	0.36	0.11	0.06	0.88	0.57	0.16	0.08
<i>Intersections on rural multilane highways</i>									
3-Leg Signalized (3SG)	26	1.17	0.25	0.14	0.04	1.53	0.39	0.20	0.08
3-Leg Minor STOP (3ST)	136	1.39	0.28	0.09	0.56	1.33	0.47	0.14	0.60
4-Leg Signalized (4SG)	23	0.98	0.27	0.14	0.09	0.79	0.16	0.16	0.30
4-Leg Minor STOP (4ST)	60	1.88	0.72	0.16	0.28	2.24	1.23	0.24	0.55
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>									
3-Leg Signalized (3SG)	41	1.30	0.25	0.12	0.02	1.32	0.43	0.18	0.02
3-Leg Signalized High Speed (3SG-HS)	34	0.98	0.29	0.13	0.56	1.14	0.75	0.24	0.56
3-Leg Minor STOP (3ST)	160	1.50	0.27	0.08	0.94	1.13	0.71	0.16	0.39
3-Leg Minor STOP High Speed (3ST-HS)	85	0.88	0.41	0.11	0.38	0.97	0.61	0.16	0.38
4-Leg Signalized (4SG)	30	1.59	0.30	0.15	0.03	1.79	0.67	0.33	0.33
4-Leg Signalized High Speed (4SG-HS)	30	0.76	0.23	0.11	0.47	0.79	0.60	0.21	0.17
4-Leg Minor STOP (4ST)	80	1.47	0.29	0.10	0.04	1.18	0.67	0.20	0.01
4-Leg Minor STOP High Speed (4ST-HS)	60	0.95	0.22	0.09	0.57	0.90	0.44	0.14	0.28
5-Leg Signalized (5SG)	4	0.67	0.01	0.16	0.25	0.89	0.01	0.26	0.25
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>									
3-Leg Signalized (3SG)	29	0.98	0.36	0.14	0.24	0.58	0.36	0.17	0.28
3-Leg Minor STOP (3ST)	29	1.05	0.18	0.12	0.10	0.61	0.14	0.15	0.03
4-Leg Signalized (4SG)	33	0.56	0.27	0.11	0.03	0.44	0.53	0.21	0.12

Site Type	No. of Sites	All Crash Severities				Fatal and Injury Crashes			
		Calibration Factor	Dispersion Parameter	CV	CURE Deviation ^a	Calibration Factor	Dispersion Parameter	CV	CURE Deviation ^a
4-Leg Minor STOP (4ST)	26	1.41	0.43	0.17	0.04	0.86	0.36	0.20	0.04
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>									
4-Leg Signalized (4SG)	16	1.55	0.06	0.11	0.06	1.86	0.01	0.15	0.06
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>									
4-Leg All-Way STOP (4AST)	13	3.06	0.29	0.20	0.08	2.22	0.96	0.39	0.08

CURE = cumulative residual; CV = coefficient of variation. ^aCURE deviation is the proportion of CURE plot ordinates outside a 2-standard deviation confidence band. Gray shading means acceptance criteria met (either $CV \leq 0.15$ or CURE deviation ≤ 0.05).

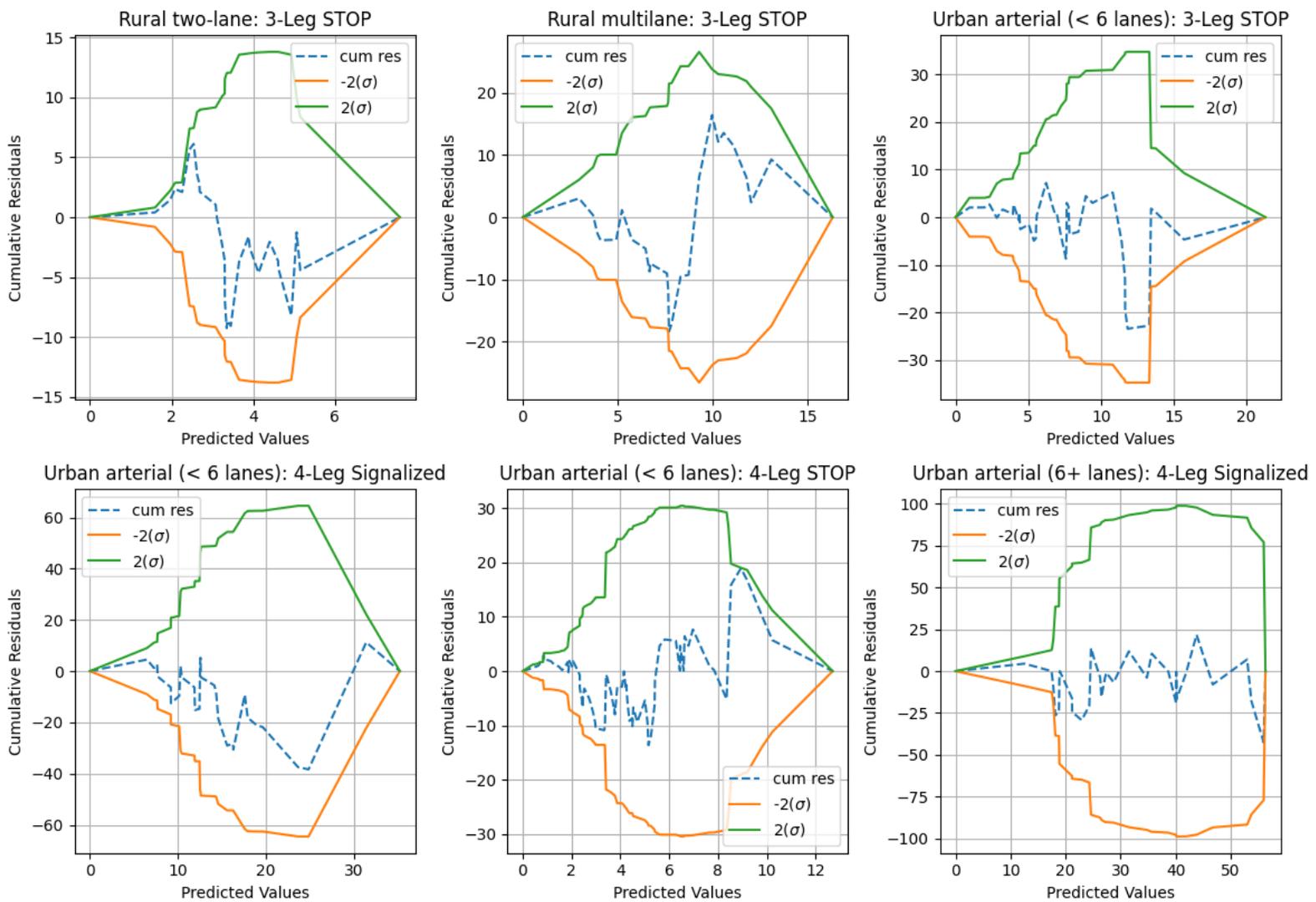


Figure 3. Example Cumulative Residual Plots Demonstrating Good Fit for Total Crash Predictions Using Calibration Factors. σ = Standard Deviation.

Table 10. Calibration Function Results

Site Type	No. of Sites	All Crash Severities			Fatal and Injury Crashes				
		Parameter Estimates			CURE Deviation ^a	Parameter Estimates			CURE Deviation ^a
		<i>a</i>	<i>b</i>	<i>k</i>		<i>a</i>	<i>b</i>	<i>k</i>	
<i>Intersections on rural two-lane, two-way roads</i>									
3-Leg Signalized (3SG)	28				0.41	0.94	0.90	0.04	
3-Leg Minor STOP (3ST)	216								
4-Leg Signalized (4SG)	54				0.60	0.58	0.73	0.02	
4-Leg Minor STOP (4ST)	113				0.78	0.84	0.55	0.07	
<i>Intersections on rural multilane highways</i>									
3-Leg Signalized (3SG)	26				1.46	0.81	0.37	0.08	
3-Leg Minor STOP (3ST)	136				0.58	0.46	0.36	0.01	
4-Leg Signalized (4SG)	23				0.91	0.09	0.02	0.04	
4-Leg Minor STOP (4ST)	60	1.87	0.44	0.58	0.02	0.98	0.20	0.80	
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>									
3-Leg Signalized (3SG)	41				1.40	1.29	0.40	0.02	
3-Leg Signalized High Speed (3SG-HS)	34				0.84	2.05	0.59	0.03	
3-Leg Minor STOP (3ST)	160				0.68	0.66	0.54	0.13	
3-Leg Minor STOP High Speed (3ST-HS)	85				0.55	0.25	0.51	0.01	
4-Leg Signalized (4SG)	30				1.53	1.46	0.58	0.07	
4-Leg Signalized High Speed (4SG-HS)	30				1.16	0.64	0.56	0.10	
4-Leg Minor STOP (4ST)	80				1.05	0.88	0.67	0.01	
4-Leg Minor STOP High Speed (4ST-HS)	60				0.87	0.51	0.35	0.02	
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>									
3-Leg Signalized (3SG)	29				0.86	0.65	0.33	0.03	
3-Leg Minor STOP (3ST)	29				0.68	0.74	0.15	0.03	
4-Leg Signalized (4SG)	33				0.20	1.33	0.51	0.03	
4-Leg Minor STOP (4ST)	26				0.88	0.87	0.35	0.04	

CURE = cumulative residual. *a* and *b* are calibration function regression coefficients; *k* is the dispersion parameter. ^a CURE deviation is the proportion of CURE plot ordinates outside a 2-standard deviation confidence band. Gray shading means acceptance criteria met (coefficient of variation ≤ 0.15 or CURE deviation ≤ 0.05).

Summary and Discussion

The updated HSM expands its intersection SPFs from 41 to more than 100, including SPFs for new configurations such as roundabouts and five-leg intersections. Because calibrating all SPFs is impractical due to limited data and resource demands, this study focused on 34 conventional intersection types with sufficient data for calibration.

More than 59,000 candidate intersections were analyzed using geospatial and database tools to identify, classify, and select suitable calibration sites. Site selection followed HSM requirements for sample size and crash data, and each chosen intersection was manually reviewed for accuracy using Google Earth.

Several intersections in the candidate list were discarded because of data quality issues (e.g., incorrect number of legs, lanes, and so on). A final dataset of 1,326 sites was assembled for calibration. A few sites had low sample sizes, and these sites were combined. In these instances, a common calibration factor was explored where appropriate, based on discussions with the technical review panel.

The analysis first developed constant calibration factors for total crashes and fatal and injury crashes. Applying the constant calibration factors developed in this study produced a good fit between predicted and observed total crash frequencies across most site types, with 20 of 21 site types that had at least a modest (more than 15) sample size meeting the HSM acceptance criteria of either CV less than or equal to 0.15 (18 of 21 sites) or percent CURE deviation less than 5% (7 of 21 sites). However, the constant calibration factors did not provide a satisfactory fit for fatal and injury crash predictions, with only 10 site types meeting the HSM acceptance criteria. Calibration functions developed in this study provided a better fit for fatal and injury crashes, with 14 of 19 site types achieving a percent CURE deviation within 5%. CURE deviations for the five remaining site types ranged between 7% and 13%. The Appendix provides a summary of the CURE plots.

It is possible that constant calibration factors were a poor fit to fatal and injury crashes because of the relatively smaller sample sizes used for these crash types, and using larger samples might give better constant calibration factor estimates. However, the effort involved might not be necessary at this time, considering the amount of work required to assemble the data and the reasonable results that the calibration functions already produced. The HSM recommends recalibration once every 3 years, so the need for adding more sites to the calibration set and recalculating constant calibration factors may be revisited at that time if, for example, data quality has improved. For now, this study recommends using constant calibration factors for total crashes and the estimated calibration functions for fatal and injury crashes. Tables 11 and 12 summarize these recommended results.

Table 11. Recommended Calibration Factors for Total Crashes

Site Type	Calibration Factor	Dispersion Parameter ^a
<i>Intersections on rural two-lane, two-way roads</i>		
3-Leg Signalized (3SG)	0.79	0.21
3-Leg Minor STOP (3ST)	1.20	0.01
4-Leg Signalized (4SG)	0.94	0.43
4-Leg Minor STOP (4ST)	0.91	0.36
<i>Intersections on rural multilane highways</i>		
3-Leg Signalized (3SG)	1.17	0.25
3-Leg Minor STOP (3ST)	1.39	0.28
4-Leg Signalized (4SG)	0.98	0.27
4-Leg Minor STOP (4ST)	1.88 ^b	0.72
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>		
3-Leg Signalized (3SG)	1.30	0.25
3-Leg Signalized High Speed (3SG-HS)	0.98	0.29
3-Leg Minor STOP (3ST)	1.50	0.27
3-Leg Minor STOP High Speed (3ST-HS)	0.88	0.41
4-Leg Signalized (4SG)	1.59	0.30
4-Leg Signalized High Speed (4SG-HS)	0.76	0.23
4-Leg Minor STOP (4ST)	1.47	0.29
4-Leg Minor STOP High Speed (4ST-HS)	0.95	0.22
5-Leg Signalized (5SG)	-	
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>		
3-Leg Signalized (3SG)	0.98	0.36
3-Leg Minor STOP (3ST)	1.05	0.18
4-Leg Signalized (4SG)	0.56	0.27
4-Leg Minor STOP (4ST)	1.41	0.43
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>		
4-Leg Signalized (4SG)	1.55	0.06
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>		
4-Leg All-Way STOP (4AST)	-	

^a For use with the empirical Bayes procedure described in the *Highway Safety Manual*. ^b Barely missed acceptance criteria (coefficient of variation = 0.16; acceptance criterion coefficient of variation ≤ 0.15). – = not a large enough sample size to develop a reliable calibration factor.

Table 12. Recommended Calibration Function Parameter Estimates for Fatal and Injury Crashes

Site Type	a	b	Dispersion Parameter
<i>Intersections on rural two-lane, two-way roads</i>			
3-Leg Signalized (3SG)	0.41	0.94	0.90
3-Leg Minor STOP (3ST)	1.03*	1.00	0.01
4-Leg Signalized (4SG)	0.60	0.58	0.73
4-Leg Minor STOP (4ST)	0.78	0.84	0.55
<i>Intersections on rural multilane highways</i>			
3-Leg Signalized (3SG)	1.46	0.81	0.37
3-Leg Minor STOP (3ST)	0.58	0.46	0.36
4-Leg Signalized (4SG)	0.91	0.09	0.02
4-Leg Minor STOP (4ST)	0.98	0.20	0.80
<i>Intersections on urban or urban arterials where each road is two way and has five lanes or fewer (2 x 2)</i>			
3-Leg Signalized (3SG)	1.40	1.29	0.40
3-Leg Signalized High Speed (3SG-HS)	0.84	2.05	0.59
3-Leg Minor STOP (3ST)	0.68	0.66	0.54
3-Leg Minor STOP High Speed (3ST-HS)	0.55	0.25	0.51
4-Leg Signalized (4SG)	1.53	1.46	0.58
4-Leg Signalized High Speed (4SG-HS)	1.16	0.64	0.56
4-Leg Minor STOP (4ST)	1.05	0.88	0.67
4-Leg Minor STOP High Speed (4ST-HS)	0.87	0.51	0.35
5-Leg Signalized (5SG)	–	–	
<i>Intersections between two two-way urban or suburban roads, at least one of which has six or more lanes (2 x 2)</i>			
3-Leg Signalized (3SG)	0.86	0.65	0.33
3-Leg Minor STOP (3ST)	0.68	0.74	0.15
4-Leg Signalized (4SG)	0.20	1.33	0.51
4-Leg Minor STOP (4ST)	0.88	0.87	0.35
<i>Intersections on urban or suburban arterials where at least one road is one way (1 x 1, 1 x 2)</i>			
4-Leg Signalized (4SG)	1.86*	1.00	0.01
<i>All-Way stop intersections on rural two-lane roads or on urban or suburban arterials</i>			
4-Leg All-Way STOP (4AST)	–	–	

* Equivalent to constant calibration factors. – = not a large enough sample size to develop a reliable calibration function; a and b = regression coefficients.

CONCLUSIONS

- *Using constant calibration factors developed in this study to adjust the HSM SPF predictions for total crashes (all severities) provided a good fit to Virginia data. However, using constant calibration factors did not provide a good fit to the predictions of fatal and injury crashes.*

Predictions for all but one conventional intersection site type studied that had at least a modest sample size (more than 15) met the HSM acceptance criteria of either CV less than or equal to 0.15 or percent CURE deviation less than 5% when total crashes were predicted. Only 10 of these same site types satisfied the HSM criteria when fatal and injury crashes were predicted.

- *Calibration functions developed in this study offered a better fit for fatal and injury crash data in Virginia compared with using constant calibration factors.* The percent of CURE plot ordinates outside the 95% confidence interval ranged between 1% and 13% with 14 out of 19 calibrated site types meeting the 5% CURE deviation threshold.

RECOMMENDATION

1. *VDOT's TOD should use the calibration results from this study when using SPFs for the conventional intersection site types contained in the HSM.* Table 11 (constant calibration factors) should be used for total crashes, and Table 12 (calibration functions) should be used for fatal and injury crashes.

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 determine the benefits of doing so. This process 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

Regarding the recommendation, VDOT's TOD will incorporate the calibration factors and calibration functions detailed in this report into the Traffic Operations and Safety Analysis Manual within 2 years of the publication of this report, subject to the publication of the HSM second edition. In the event of HSM publication delays or Traffic Operations and Safety Analysis Manual update delays, the Assistant Division Administrator for Safety will encourage and promote the application of the results through avenues that may include (1) publishing the calibration factors and functions on the TOD website, (2) making the information available to consultants and VDOT staff working on related VDOT projects, and (3) presenting it at the Traffic Operations Data and Tools Community of Practice meetings.

Benefits

Implementing the recommendation will significantly improve the accuracy of quantitative safety analyses for conventional intersections, resulting in more reliable and cost-effective safety investment decisions. Calibration is important because safety conditions may differ significantly among jurisdictions and change over time. The application of uncalibrated or

inappropriately calibrated SPFs may produce misleading results, compromise safety outcomes, and lead to inappropriate design decisions.

This study demonstrated that calibration factors for total crashes ranged from 0.56 to 1.88, equivalent to differences of 44% to 88% between calibrated and uncalibrated models. These discrepancies are large enough to materially influence project rankings in the Highway Safety Improvement Program or other analyses that use HSM methods. In practice, a difference of two to three crashes per year can determine whether a Highway Safety Improvement Program application is funded or not. Using uncalibrated SPFs increases the risk that high-value projects are not funded, whereas lower value projects may incorrectly rise to the top. Using the more accurate prediction, as this research recommends, will improve the selection of Highway Safety Improvement Program projects. This study's recommendation directly supports these benefits. Specifically, the benefits of implementing the recommendation would be higher accuracy of safety predictions.

Note that even though calibration can be a relatively low-cost analytical enhancement that leads to more effective project selections, the calibrated model may not necessarily yield higher crash reduction gains per dollar spent just because it is more accurate than the uncalibrated model—model accuracy is just one component of cost-benefit analysis. The models are tools for prediction, but the actual “gain” comes from the effectiveness of the interventions based on those predictions.

ACKNOWLEDGMENTS

The author thanks the following people who served on the technical review panel for this study: Stephen Read, Project Champion, VDOT TOD; Whoibin Chung, VDOT TOD; Shan Di, VDOT TOD; and Ben Cottrell, Virginia Transportation Research Council.

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APPENDIX

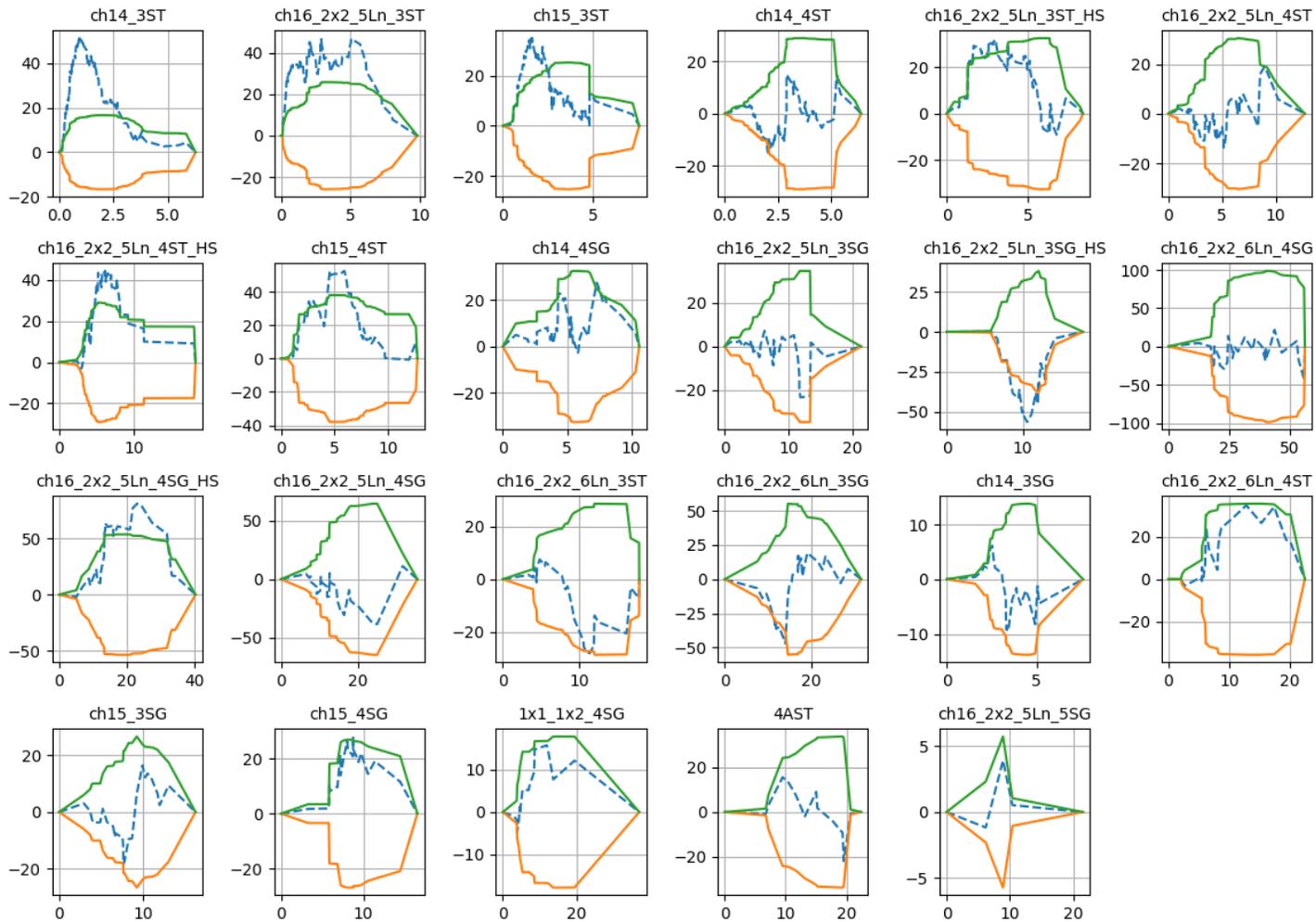


Figure A1. Cumulative Residual Plots for Total Crash Predictions Using Calibration Factors. Vertical axes = cumulative residuals; horizontal axes = predicted values; blue dashed line = cumulative residual plot; green and orange lines are the upper and lower 2 standard deviation confidence limits, respectively; ch14_ = rural two-lane road; ch15_ = rural multilane highway; ch16_ = urban or Suburban arterial; 3ST = 3-leg stop control; 4SG = 4-leg signalized; 2x2_6Ln = two two-way roads, at least one of which has six or more lanes; 2x2_5Ln = 2 two-way roads, each with at most five lanes; 1x1_1x2 = at least one one-way road; 4AST = 4-leg all-way stop.

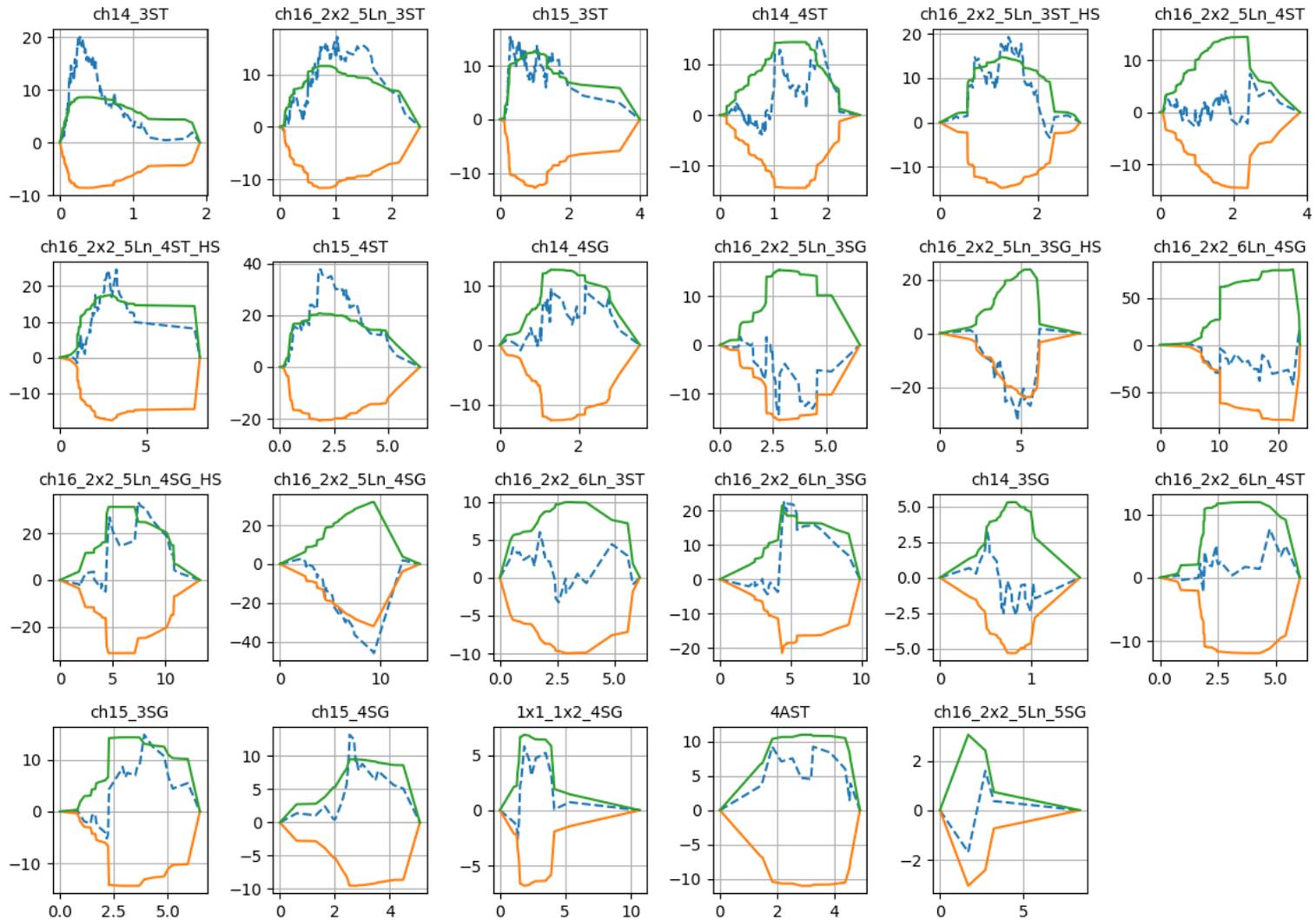


Figure A2. Cumulative Residual Plots for Fatal and Injury Crash Predictions Using Calibration Factors. Vertical axes = cumulative residuals; horizontal axes = predicted values; blue dashed line = cumulative residual plot; green and orange lines are the upper and lower 2 standard deviation confidence limits, respectively; ch14_ = rural two-lane road; ch15_ = rural multilane highway; ch16_ = urban or suburban arterial; 3ST = 3-leg stop control; 4SG = 4-leg signalized; 2x2_6Ln = 2 two-way roads, at least one of which has six or more lanes; 2x2_5Ln = two two-way roads, each with at most five lanes; 1x1_1x2 = at least one one-way road; 4AST = 4-leg all-way stop.

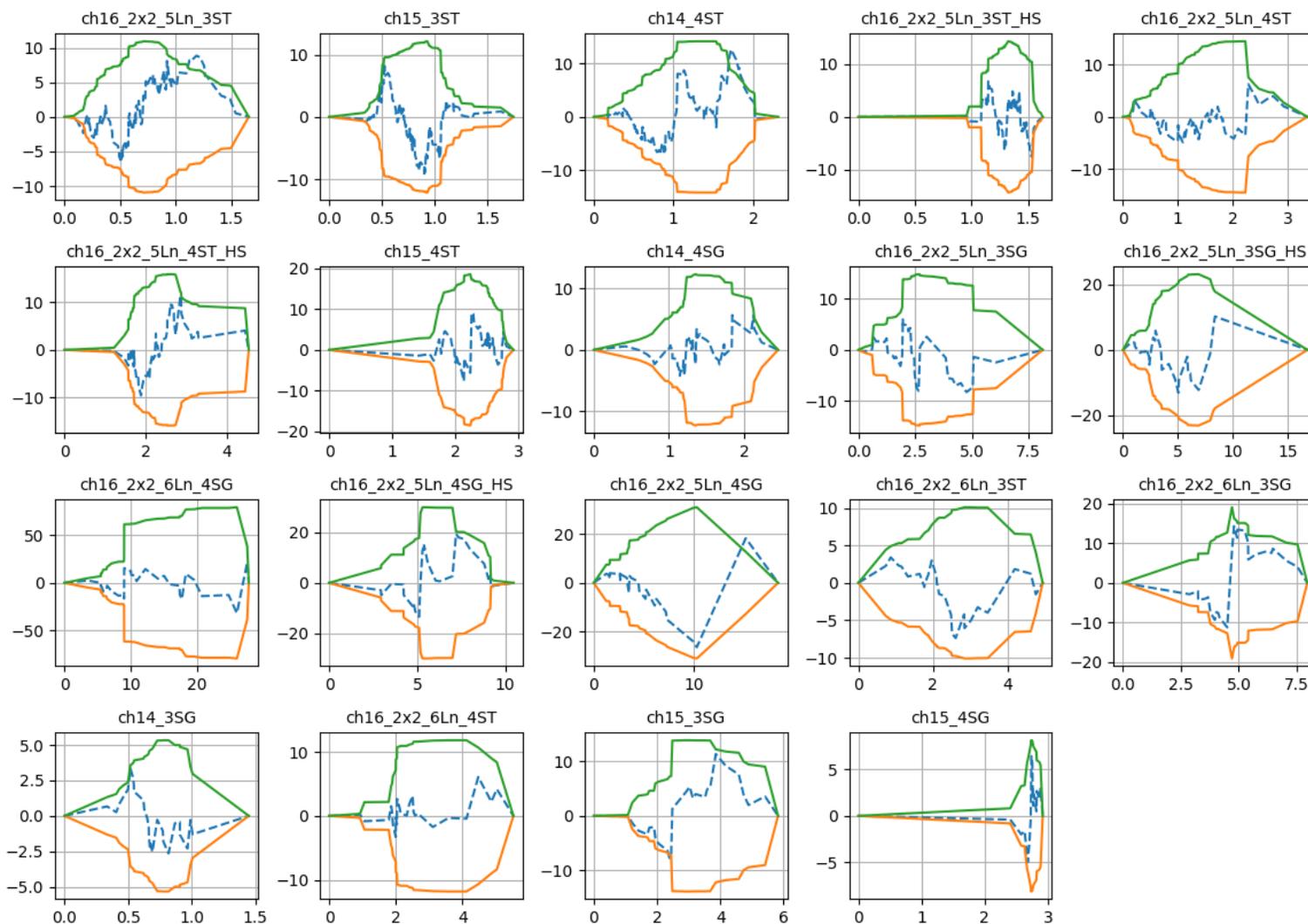


Figure A3. Cumulative Residual Plots for Fatal and Injury Crash Predictions Using Calibration Functions. Vertical axes = cumulative residuals; horizontal axes = predicted values; blue dashed line = cumulative residual plot; green and orange lines are the upper and lower 2 standard deviation confidence limits, respectively; ch14 = rural two-lane road; ch15 = rural multilane highway; ch16 = urban or suburban arterial; 3ST = 3-leg stop control; 4SG = 4-leg signalized; 2x2_6Ln = two two-way roads, at least one of which has six or more lanes; 2x2_5Ln = two two-way roads, each with at most five lanes; 1x1_1x2 = at least one one-way road.