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Development of Safety Performance Functions for Multilane Highway and Freeway Segments Maintained by the Virginia Department of Transportation

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16. Abstract:

The Virginia Department of Transportation (VDOT) adopted the software Safety Analyst™ as its highway safety management tool in 2009. One of the requirements for implementation of Safety Analyst is to have appropriate safety performance functions (SPFs) reflecting Virginia conditions. The purpose of this study was to develop such SPFs for multilane highway and freeway segments that could replace Safety Analyst's default SPFs. Five years (2004-2008) of data collected from 20,235 multilane highway segments and 2,905 directional freeway segments in Virginia were used in the development of the SPFs. Statewide SPFs were developed for 4 subtypes of multilane highway segments and 10 subtypes of freeway segments. VDOT district-group SPFs were developed for 4 subtypes of multilane highway segments.

The default SPFs in Safety Analyst were found to be different than the developed Virginia SPFs with respect to their curve shapes, and, as a result, adjusting the default SPFs to Virginia conditions by calibration factors resulted in inaccurate crash predictions at low and high volumes of annual average daily traffic. Thus, the Virginia-specific statewide SPFs developed in this study should be used when implementing Safety Analyst in Virginia.

Although the shapes of the multilane highway segment SPFs were found to vary across VDOT districts, incorporating variations through the creation of new subtypes was found to be inappropriate for the current version of Safety Analyst. As a consequence, district-group SPFs for the multilane highway segments cannot be implemented in Safety Analyst. However, all SPFs developed in this study, including district-group SPFs, can be implemented without the use of Safety Analyst. Therefore, use of the statewide SPFs developed in this study is recommended when Safety Analyst can be used and use of the statewide or district-group SPFs developed in this study is recommended when implementation of Safety Analyst is not feasible.

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FINAL REPORT

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ABSTRACT

The Virginia Department of Transportation (VDOT) adopted the software Safety Analyst™ as its highway safety management tool in 2009. One of the requirements for implementation of Safety Analyst is to have appropriate safety performance functions (SPFs) reflecting Virginia conditions. The purpose of this study was to develop such SPFs for multilane highway and freeway segments that could replace Safety Analyst's default SPFs. Five years (2004-2008) of data collected from 20,235 multilane highway segments and 2,905 directional freeway segments in Virginia were used in the development of the SPFs. Statewide SPFs were developed for 4 subtypes of multilane highway segments and 10 subtypes of freeway segments. VDOT district-group SPFs were developed for 4 subtypes of multilane highway segments.

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Although the shapes of the multilane highway segment SPFs were found to vary across VDOT districts, incorporating variations through the creation of new subtypes was found to be inappropriate for the current version of Safety Analyst. As a consequence, district-group SPFs for the multilane highway segments cannot be implemented in Safety Analyst. However, all SPFs developed in this study, including district-group SPFs, can be implemented without the use of Safety Analyst. Therefore, use of the statewide SPFs developed in this study is recommended when Safety Analyst can be used and use of the statewide or district-group SPFs developed in this study is recommended when implementation of Safety Analyst is not feasible.

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INTRODUCTION

In 2009, the Virginia Department of Transportation (VDOT) adopted the software Safety Analyst™ as the state's highway safety management tool. Safety Analyst was developed by the Federal Highway Administration (FHWA) with participation from selected state and local agencies and is distributed by the American Association of State Highway and Transportation Officials (AASHTO) (FHWA, 2009a). Safety Analyst has the capability to identify sites at a high risk for crashes, prioritize the identified sites based on different criteria, recommend proper crash countermeasures, and perform economic appraisals (FHWA, 2009b).

One of the core requirements for Safety Analyst is appropriate safety performance functions (SPFs) (FHWA, 2009c). An SPF is a function of annual average daily traffic (AADT) and length for segments and two AADTs of crossing streets for intersections, and it is used to predict the number of crashes at a site under given conditions (e.g., AADT and segment length) so that the safety performance of the site can be assessed. Safety Analyst is equipped with default SPFs developed with the use of data from several states participating in the Highway Safety Information System. Since Virginia does not participate in this system, no Virginia data were used in the development of Safety Analyst's default SPFs (hereinafter "default SPFs"). For multilane highways, the default SPFs were developed with the use of data from four states: Minnesota, North Carolina, Ohio, and Washington. For freeways, the default SPFs were developed with the use of data from three states: Minnesota, California, and Washington.

In order to use the default SPFs in Virginia, one would need to assume that driving environments and behaviors related to traffic safety in Virginia were similar to those in the states whose data were used to develop the default SPFs. If it is the case that they are not similar, use of the default SPFs would entail the risk that the resulting safety evaluation would lead to inappropriate identification and prioritization of sites for safety improvements in Virginia. To ensure that Virginia conditions are properly reflected, SPFs for Safety Analyst need to be customized using local data.

There are two ways of customizing SPFs, both using local data: (1) calibrating the default SPFs and (2) developing a new set of SPFs. When Safety Analyst is installed and connected to a local database, it automatically calibrates the default SPFs (FHWA, 2009c). However, this calibration does not change the fundamental shapes of the curves of the default SPFs but instead shrinks or enlarges the curves vertically to fit to the local conditions while keeping the shapes of the SPF curves. Research (e.g., Garber et al. [2010]; Garber and Rivera [2010]) has shown that the shapes of SPF curves could vary significantly from state to state.

The second way of customizing SPFs using local data would require additional effort since an entirely new set of SPFs would need to be developed (FHWA, 2009c). However, this method guarantees that the developed SPFs would reflect driving environments and behaviors associated with traffic safety in Virginia. A Virginia study on intersections (Garber and Rivera, 2010) found that SPFs developed using Virginia data are significantly different from those of other states. Thus, it is anticipated that SPFs developed using Virginia data for freeways and multilane highways would be different from the default SPFs of Safety Analyst.

There are three predefined facility types in Safety Analyst: intersection, segment, and ramp (FHWA, 2009c). Varying numbers of subtypes are defined for each facility type, and one SPF is desirable for each subtype in each facility type. Under the segment facility type, there are 17 subtypes defined in Safety Analyst as follows (FHWA, 2009c):

1. rural two-lane highway segments
2. rural multilane undivided highway segments
3. rural multilane divided highway segments
4. rural freeway segments—4 lanes
5. rural freeway segments—6+ lanes
6. rural freeway segments within an interchange area—4 lanes
7. rural freeway segments within an interchange area—6+ lanes
8. urban two-lane arterial segments
9. urban multilane undivided arterial segments
10. urban multilane divided arterial segments
11. urban one-way arterial segments
12. urban freeway segments—4 lanes
13. urban freeway segments—6 lanes
14. urban freeway segments—8+ lanes
15. urban freeway segments within an interchange area—4 lanes
16. urban freeway segments within an interchange area—6 lanes
17. urban freeway segments within an interchange area—8+ lanes.

Of the 17 subtypes, Virginia-specific SPFs have already been developed (Garber et al., 2010) for 2 subtypes: rural two-lane highway segments, and urban two-lane arterial segments. Since a third subtype, urban one-way arterial segments, is mostly found in roadway networks within cities and VDOT does not have AADT and roadway inventory data for these segments, development of SPFs for this subtype is not being considered at present. This study focused on the remaining 14 subtypes of multilane highways and freeways.

PURPOSE AND SCOPE

The purpose of this study was to develop SPFs for 14 freeway and multilane highway segments in Virginia that can replace the default SPFs in Safety Analyst.

Specifically, the scope of the study was limited to the following 14 subtypes of segment facility type:

For multilane highways:

- rural multilane undivided highway segments
- rural multilane divided highway segments
- urban multilane undivided arterial segments
- urban multilane divided arterial segments.

For freeway highways:

- rural freeway segments—4 lanes
- rural freeway segments—6+ lanes
- rural freeway segments within an interchange area—4 lanes
- rural freeway segments within an interchange area—6+ lanes
- urban freeway segments—4 lanes
- urban freeway segments—6 lanes
- urban freeway segments—8+ lanes
- urban freeway segments within an interchange area—4 lanes
- urban freeway segments within an interchange area—6 lanes
- urban freeway segments within an interchange area—8+ lanes.

Arterials are called "highways" hereinafter in this study.

METHODS

Data Preparation

Overview

The researchers obtained data from VDOT's Oracle-based roadway management system, i.e., Roadway Network System (RNS), which recently replaced the Highway Traffic Records Information System. RNS currently serves as the official repository of VDOT's business data for internal management and reporting. RNS facilitates a relational database that provides universal enterprise data access and links geospatial data and business attributes to the roadway centerlines.

Records from three RNS subsystems, i.e., Roadway Inventory (RDI), Accident (ACC), and Traffic Monitoring System (TMS), were used to produce data for this study. RDI contains information on about 62,000 centerline miles of public roadways in Virginia including cross-section characteristics, functional classification, administrative information, and ownership. ACC contains historical crash records including more than 70 elements of crash-, occupant-, and vehicle-related characteristics extracted from police crash reports (i.e., the FR300 form). TMS contains historical traffic count data (e.g., AADT) and the locations of the traffic counters. To extract the study data, the researchers identified eligible segments of multilane highways and freeways by screening the RDI records for data for 5 years (2004–2008) and then merging the TMS and ACC records for those years to the identified segments.

Identification of Segment Crash and Facility Type

Identify Segment Crashes

An *intersection crash* is defined as a crash inside 250 feet from the center of an intersection in Virginia. Thus, all crashes excluding intersection crashes were identified as *segment crashes.*

Identify Multilane Highways

A *multilane highway* in Safety Analyst refers to a road with four or more through lanes excluding one-way roads, bridges, tunnels, causeways, transitions, and the primary forms of access and egress. A multilane highway segment is classified into the four subtypes (rural/urban/undivided/divided) according to the level of mobility, land access, and physical location. A specific procedure in RNS for identifying and classifying multilane highway segments is presented later.

Identify Freeways and Interchange Areas

A *freeway* is generally defined as a controlled-access highway designed exclusively for high-speed vehicle traffic that is free of at-grade crossings with other roads, railways, or pedestrian paths. In Virginia, *freeway* generally refers to an interstate highway. For implementing Safety Analyst, a freeway segment should be classified as either a segment within an interchange area or a segment outside an interchange area; an *interchange area* is defined as the area between gores of entrance/exit ramps. To classify each segment, a set of special Structured Query Language (SQL) codes was developed. An interchange area identified by the SQL codes may not be exactly matched with the definition of an interchange area since the area identification was performed based on highway links established in RDI. A specific procedure in RNS for identifying and classifying freeway segments is presented later.

Data Analysis

A regression analysis was used to develop SPFs with the functional form required for Safety Analyst. The required form of SPFs and the regression model used in this study are described here.

Functional Form of SPFs

The following functional form of a segment SPF was used in this study because it is required for Safety Analyst (Exelis Inc., 2013):

$$E(Crash\ Frequency_{i,t}) = exp(\alpha + \beta_1 \times \ln(AADT_{i,t}) + \ln(Length_{i,t})) \qquad \text{[Eq. 1]}$$
$$= e^{\alpha} \times AADT_{i,t}^{\beta_1} \times Length_{i,t}$$

where

i = segment index
t = year index
$E(\cdot)$ = expectation
$Crash\ Frequency_{i,t}$ = total number of crashes on segment i in year t
$AADT_{i,t}$ = annual average daily traffic volume on segment i in year t
$Length_{i,t}$ = length of segment i in year t
α and β_1= coefficient parameters to be estimated.

When the AADT and length of a segment are given, a predicted annual crash frequency per mile per year of that segment can be computed by entering the given AADT and segment length into Equation 1 with estimated parameters. Since the data on crash frequency, AADT, and length for freeway segments are directional, the AADT and length entered into the equation should be for one direction; thus, the resulting predicted crash frequency will be for one direction. Otherwise, all the entering input values for multilane highway segments are for two directions. Thus, the resulting predicted frequency is for two directions. The coefficient parameters are estimated by a regression analysis described next.

Regression Analysis for SPFs

An SPF with the functional form specified in Equation 1 can be estimated with the use of a few regression model types such as a classical linear model with a log-transformed dependent variable and the Poisson model. Among them, a negative binomial model was selected for this study in accordance with a recommendation in *Safety Analyst User's Manual* (Exelis Inc., 2013). The negative binomial regression model is the most often used model in performing a regression analysis on traffic crash data of individual sites because the dependent variable (e.g., annual crash frequency at a site) is a non-negative integer and a conditional variance of the dependent variable is often larger than a conditional mean, known as overdispersion. The specification of the negative binomial regression model used in this study is written as follows:

$$Pr(Crash\ Frequency_{i,t} | AADT_{i,t}, Length_{i,t})$$
$$= \frac{exp[-E(Crash\ Frequency_{i,t}) \times u_{i,t}] \times [E(Crash\ Frequency_{i,t}) \times u_{i,t}]^{Crash\ Frequency_{i,t}}}{(Crash\ Frequency_{i,t})!} \qquad \text{[Eq. 2]}$$

and $u_{i,t} \sim Gamma(1/k\,, 1/k)$

where

$Pr(\cdot)$ = probability
$u_{i,t}$ = random term allowing the conditional variance to be larger than the conditional mean
k = negative binomial dispersion parameter to be estimated
$E\left(Crash\ Frequency_{i,t}\right)$ = exponential mean function of $AADT_{i,t}$ and $Length_{i,t}$, defined in Equation 1.

Since the study data were collected on the same segments over the 5 years, they form panel data (also called repeated measures or cross-sectional time-series data). If a common correlation pattern in annual crash frequencies (dependent variable) exists across the segments over the 5 years, the pattern can be used to estimate the model more accurately, which is a benefit of using panel data rather than cross-sectional data. To take advantage of such a benefit, a preset correlation structure can be placed on top of the model specification in Equation 1, resulting in a panel negative binomial regression model. The panel model was estimated using the generalized estimating equation (GEE). Among the most popular four correlation structures, one best fitting the study data was selected based on the quasi-likelihood information criterion (QIC) in which a better model produces a smaller value. GEE, the four correlation structures, and QIC are described in Appendix A. The negative binomial dispersion parameter was estimated without using GEE.

Non-Parametric Regression Analysis for SPFs

As seen in Equation 1, the model specification for SPFs including the functional form and the entering predictors was fixed in accordance with the SPF requirement for Safety Analyst (Exelis Inc., 2013). An assessment of the functional form was attempted using a penalized smooth B-spline model belonging to a class of non-parametric regression models. The penalized smooth B-spline model and fitted models are presented in Appendix B.

RESULTS

All statistical analyses including basic descriptive statistics, development of statewide and district-group SPFs, and the penalized smooth B-spline model were performed using SAS 9.2. A set of SQL codes was developed for retrieving and formatting data suitable for statistical analysis.

Data Preparation

Procedure for Multilane Highway Segments

The procedure for data preparation for multilane highway segments is depicted in Figure 1.

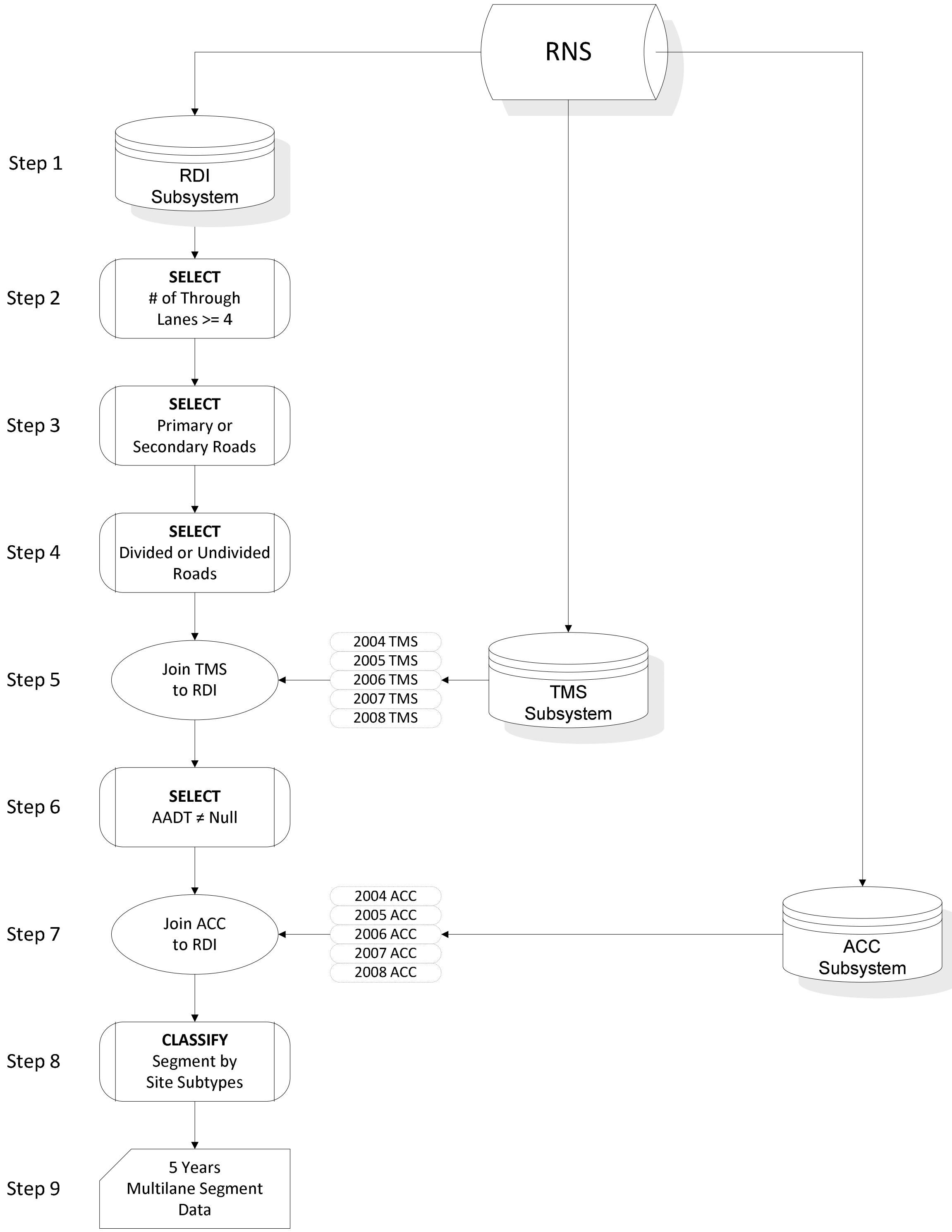


Figure 1. Procedure for Data Preparation for Multilane Highway Segments. RNS = Roadway Network System; RDI = Roadway Inventory; TMS = Traffic Management System; ACC = Accident.

The steps in the procedure are as follows.

1. *Access records of road segments in RDI.*

2. *Select segments with four or more through lanes.* This extracts multilane segments on all public roads.

3. *Select segments on primary or secondary roads and not connected to ramps.* This excludes segments on interstate highways and segments with the primary forms of access or egress points.

4. *Select two-way segments being divided or undivided.* This excludes segments of one-way roads, bridges, tunnels, causeways, or transitions.

5. *Extract 2004-2008 AADT records from TMS and merge the extracted AADTs to the multilane segments selected in Step 4.*

6. *Eliminate segments with missing or invalid records of AADTs.*

7. *Extract 2004-2008 crash records from ACC and merge the extracted records to the remaining segments selected in Step 6.* In extracting crash records, crashes inside 250 feet from the center of intersections, defined as intersection crashes in Virginia, are excluded.

8. *Classify the segments into four subtypes using information in AREA (urban and rural) and FACILITYTYPE (divided and undivided).*

9. *Five-year data for multilane highway segments are formed.*

Procedure for Freeway Segments

The data preparation procedure for freeway segments is depicted in Figure 2.

The steps in the procedure are as follows:

1. *Access records of road segments in RDI.*

2. *Select segments on interstate highways.* In general, *freeways* refer to *interstate highways i*n Virginia.

3. *Classify the segments into two types: within and outside interchange areas.* A special SQL code was developed for this classification.

4. *Extract 2004-2008 AADT records from TMS and merge the extracted AADTs to the freeway segments selected in Step 3.*

5. *Eliminate segments with missing or invalid records of AADTs.*

6. *Extract 2004-2008 crash records from ACC and merge the extracted records to the remaining segments selected in Step 5.*

7. *Classify the segments into 10 subtypes using AREA (Urban and Rural), FACILITYTYPE (Divided and Undivided), NUMBEROFLANES (Number of through lanes), and the classification made in Step 3.*

8. *Five-year data for freeway segments are formed.*

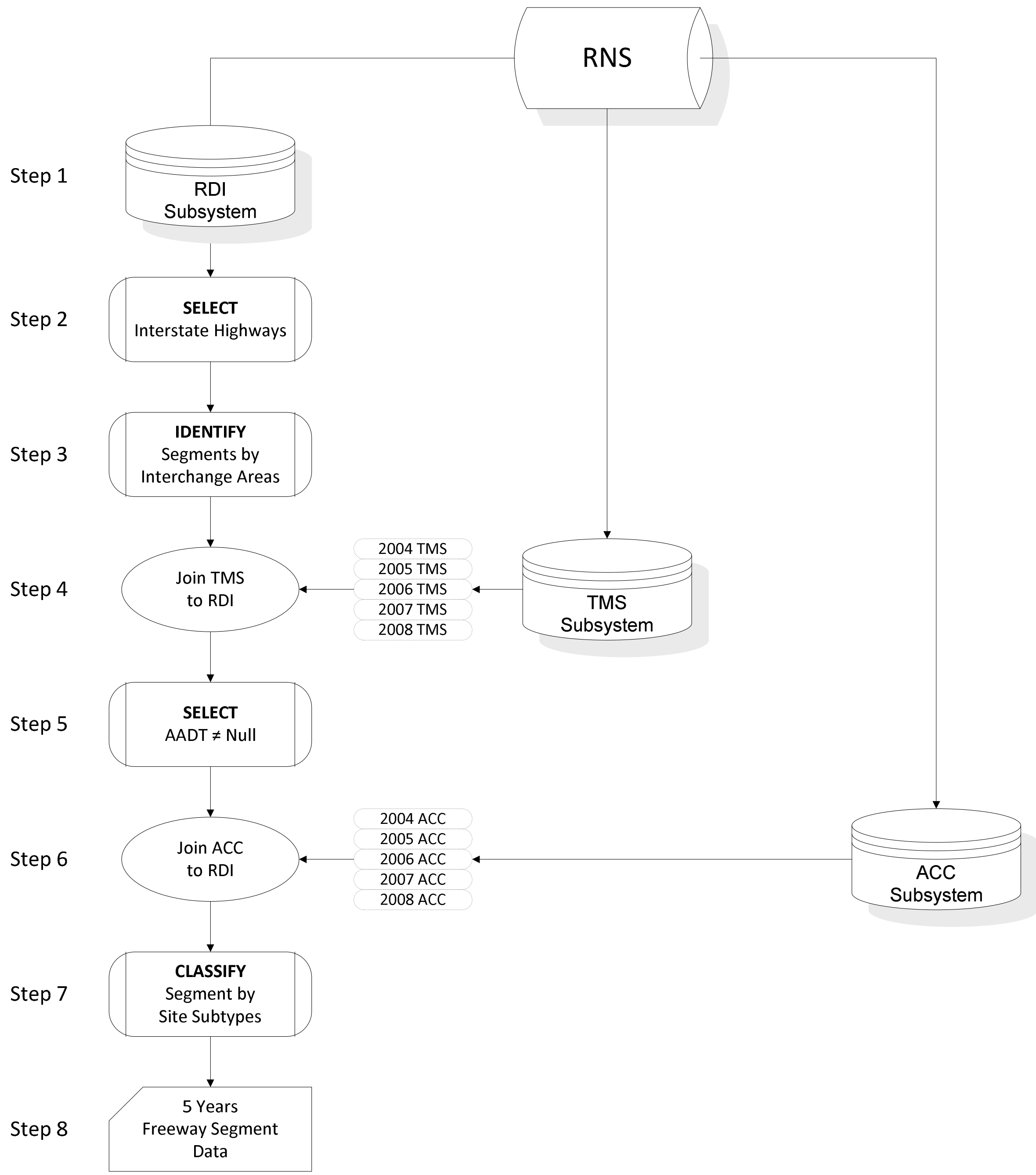


Figure 2. Procedure for Data Preparation for Freeway Segments. RNS = Roadway Network System; RDI = Roadway Inventory; TMS = Traffic Management System; ACC = Accident.

Data Summary

The study data were formed through the procedures depicted in Figures 1 and 2 and were further prepared for statistical analysis using SAS 9.2. Table 1 shows summary statistics of the final data by subtype in the order of the subtype code to be in line with the default SPF tables in *Safety Analyst User's Manual* (Exelis Inc., 2013). The 5-year (2004-2008) data were used to calculate the statistics, whereas 1-year (2008) data were used to calculate the number and total mileage of segments because the same segments were found five times in the 5-year data.

Table 1. Basic Descriptive Statistics of the Study Data (2004-2008)

Site Subtype Code	Site Subtype Description	No. of Sites (Total Mileage)[a]	No. of Records	Variable[b]	Mean	Std. Dev.	Min.	Max.
102	Rural multilane undivided highway segments	850 (168 mi)	4,249	AADT	11,002	6,215	8	39,520
				LENGTH	0.20	0.31	0.01	3.83
				TOTCRH	0.39	1.04	0	17
				FIJCRH	0.15	0.52	0	8
103	Rural multilane divided highway segments	4,689 (1,531 mi)	23,443	AADT	12,725	7,380	81	55,026
				LENGTH	0.33	0.43	0.01	8.59
				TOTCRH	0.75	1.56	0	27
				FIJCRH	0.30	0.76	0	14
104	Rural freeway segments—4 lanes	639 (1,088 mi)	3,195	AADT	17,052	5,956	3,745	36,638
				LENGTH	1.70	1.58	0.01	8.54
				TOTCRH	4.57	5.28	0	43
				FIJCRH	1.60	2.12	0	22
105	Rural freeway segments—6+ lanes	44 (89 mi)	220	AADT	36,548	11,132	16,807	58,820
				LENGTH	2.03	1.81	0.02	7.17
				TOTCRH	10.32	12.75	0	83
				FIJCRH	3.41	4.46	0	34
106	Rural freeway segments within an interchange area—4 lanes	369 (113 mi)	1,845	AADT	17,570	6,039	3,258	36,638
				LENGTH	0.31	0.16	0.01	1.31
				TOTCRH	1.29	1.62	0	15
				FIJCRH	0.42	0.74	0	6
107	Rural freeway segments within an interchange area—6+ lanes	22 (6 mi)	110	AADT	39,187	9,878	21,720	58,820
				LENGTH	0.27	0.10	0.05	0.43
				TOTCRH	2.58	2.87	0	18
				FIJCRH	0.82	1.12	0	5
152	Urban multilane undivided arterial segments	4,280 (508 mi)	21,401	AADT	16,007	10,799	19	71,444
				LENGTH	0.12	0.13	0.01	2.41
				TOTCRH	0.37	1.29	0	30
				FIJCRH	0.14	0.57	0	14
153	Urban multilane divided arterial segments	10,416 (1,448 mi)	52,082	AADT	26,309	16,571	23	113,552
				LENGTH	0.14	0.19	0.01	4.4
				TOTCRH	0.69	2.10	0	50
				FIJCRH	0.24	0.83	0	16
155	Urban freeway segments—4 lanes	362 (254 mi)	1,810	AADT	29,546	12,691	4,902	74,102
				LENGTH	0.70	0.76	0.01	5.56
				TOTCRH	5.62	9.18	0	124
				FIJCRH	1.72	2.76	0	37
156	Urban freeway segments—6 lanes	403 (223 mi)	2,015	AADT	46,739	21,865	9,184	97,868
				LENGTH	0.58	0.68	0.01	4.17
				TOTCRH	7.54	11.55	0	88
				FIJCRH	2.42	3.91	0	33

157	Urban freeway segments—8+ lanes	207 (104 mi)	1,035	AADT	65,874	16,629	23,937	100,735
				LENGTH	0.50	0.49	0.01	2.1
				TOTCRH	8.77	9.88	0	75
				FIJCRH	3.06	3.65	0	31
158	Urban freeway segments within an interchange area—4 lanes	326 (73 mi)	1,630	AADT	29,803	14,976	5,163	88,893
				LENGTH	0.22	0.19	0.01	1.28
				TOTCRH	2.69	4.46	0	45
				FIJCRH	0.82	1.50	0	17
159	Urban freeway segments within an interchange area—6 lanes	369 (90 mi)	1,845	AADT	49,973	20,971	10,118	97,868
				LENGTH	0.24	0.26	0.01	2.21
				TOTCRH	6.01	9.84	0	116
				FIJCRH	1.90	3.60	0	46
160	Urban freeway segments within an interchange area—8+ lanes	164 (37 mi)	820	AADT	67,745	16,312	23,937	102,973
				LENGTH	0.22	0.25	0.01	2.05
				TOTCRH	6.38	6.35	0	38
				FIJCRH	2.25	2.50	0	15

All values of multilane highways are for two directions (except LENGTH being a centerline length), and those of freeways are for one direction. Std. Dev. = standard deviation; Min. = minimum; Max. = maximum.
[a] All segments were found in each of 5 years and counted only once to calculate the number of segments and total mileage. For freeways, the number of directional segments and total directional mileage are reported.
[b] AADT = annual average daily traffic (vehicles per day); TOTCRH = annual number of total crashes per year per segment; FIJCRH = annual number of fatal and injury crashes per year per segment.

It should be emphasized that data for multilane highway segments are for two directions and those for freeway segments are for one direction. Thus, for example, the total mileage for multilane highways is in centerline miles and that for freeways is in directional miles. As another example, TOTCRH (total crash frequency per year per segment) and AADT of freeways are for one direction and those of multilane highways are for both directions combined. The study data included 20,235 multilane highway segments totaling 3,655 centerline miles and 2,905 directional freeway segments (1,655 and 1,250 outside and within an interchange area, respectively) totaling 2,087 directional miles (1,768 and 319 miles outside and within an interchange area, respectively).

SPF Development

Statewide SPFs

Statewide SPFs were developed using the panel negative binomial regression models described previously. GEE was employed to estimate the panel models, and the best correlation structure was selected based on the QIC value for each subtype. The final statewide SPFs for multilane highway and freeway segments are presented in Table 2 (for total crashes) and Table 3 (for fatal and injury crashes). Corresponding default SPFs of Safety Analyst (FHWA, 2010) are also presented for comparison. The SPFs shown for Virginia can replace the default SPFs shown for the other states.

Most of the coefficient parameters (i.e., α, β_1, and d) of the Virginia-specific SPFs are statistically significant at the 0.05 significance level (i.e., 95% confidence level). The parameter α in total crash SPFs of (1) rural freeway segments within an interchange area—6+ lanes and (2) urban freeway segments—8+ lanes is not statistically significant at the 0.05 level. The parameters α and β_1 in the fatal and injury crash SPF of rural freeway segments within an interchange area—6+ lanes are not statistically significant at the 0.1 level.

The parameter α is not of much concern since it acts as a calibration factor adjusting the SPF predictions toward observed crash frequencies under average existing conditions. It is somewhat similar to an intercept term in a classical linear regression and usually remains in the model although not being statistically significant unless there is a strong reason for exclusion. The parameter β_1, however, determines the SPF shape, and thus its statistical significance is of importance. The parameter being statistically non-significant means that AADT is not associated with the crash frequency. This means that the prediction curve corresponding to AADTs is flat at an average of observed crash frequencies.

The parameter β_1 in the fatal and injury crash SPF of rural freeway segments within an interchange area—6+ lanes is statistically not significant at the significance level recommended for segments (i.e., 0.1) when agency-specific SPFs are developed (AASHTO, 2013a); it is statistically significant at the 0.2 level that is recommended for the minor road AADT term of intersection SPFs. This is presumably because of a small sample size (i.e., 22 directional segments totaling 6 directional miles). This means that the *p*-value of the parameter estimate (i.e., 0.18) would likely become smaller, thus statistically more significant, if more such segments were included in the study data.

With the current sample size, a choice should be made between a flat prediction curve meaning the removal of AADT from the model and a positive-slope prediction curve meaning the inclusion of AADT in the model although the *p*-value of β_1 does not meet the recommended cutoff *p*-value of 0.1. The latter was selected for this study because the current *p*-value of β_1 (i.e., 0.18) is (1) still below the level recommended for the minor road AADT of intersection SPFs and (2) unlikely attributable to the absence of the crash frequency–AADT relationship but likely attributable to the small sample size, which is supported by all other SPFs showing a statistically significant β_1 at the 0.05 level. Thus, the model having both constant and AADT terms was determined to be final for the fatal and injury crash SPF of rural freeway segments.

In general, Virginia models have lower Freeman-Tukey R^2 (R_{FT}^2) values than the default models for the same subtype. This indicates that AADT plays a greater role in predicting crash frequencies of multilane and freeway segments in the other states whose data were used to develop the default SPFs than in Virginia. In other words, predicting crash frequencies using AADT is more difficult in Virginia than in the other states. This implies that factors other than AADT may be more influential on crash occurrence in Virginia than in those states. It should be noted that the higher R_{FT}^2 values of the default models compared to Virginia models do not mean that the default models would perform better in Virginia but do mean that AADT is more closely associated with crash frequency in those states than in Virginia.

Among the Virginia models, the R_{FT}^2 values varied considerably across subtypes within each functional class (i.e., freeway and multilane highway), and this also should be interpreted as similar to the previous case. For the example of freeway SPFs, a change in AADT reflects quite well a change in the observed total crash frequency for rural segments with 6+ lanes ($R_{FT}^2 = 70.5$) but does not do so for urban segments with 6 lanes (R_{FT}^2 = 5 1.9) or 8+ lanes ($R_{FT}^2 = 25.9$).

Based on the $R_{FT}{}^2$ values, crash frequencies for urban segments appear more difficult to predict than for rural counterparts on multilane highways and freeways except segments within an interchange area. Crash frequencies for undivided segments appear more difficult to predict than for divided counterparts on multilane highways. These findings are intuitive because driving environments on urban and undivided segments are anticipated to be more complex than on rural and divided counterparts, respectively, and thus predicting a crash frequency of a segment by use of only the AADT of the segment is more challenging for urban and undivided segments than for rural and divided segments, respectively.

For application of the developed statewide SPFs, the following equations should be used in conjunction with the Virginia-specific parameter estimates shown in Tables 2 and 3:

For freeway segments, Equation 3 should be used.

$$\begin{aligned}&Predicted\ crash\ frequency\ per\ year\ per\ direction\\ &= e^{\alpha} \times AADT_{One\ Direction}^{\beta_1} \times Segment\ Length_{One\ Direction}\end{aligned} \qquad \text{[Eq. 3]}$$

For multilane highway segments, Equation 4 should be used.

$$\begin{aligned}&Predicted\ crash\ frequency\ per\ year\\ &= e^{\alpha} \times AADT_{Two\ Directions}^{\beta_1} \times Segment\ Length_{Centerline}\end{aligned} \qquad \text{[Eq. 4]}$$

It should be noted that the default SPFs are for two directions for both multilane highways and freeways; thus, input AADTs and output predicted crash frequencies are for both directions.

The Freeman-Tukey R^2 coefficient was used to represent goodness of fit of the estimated models and was calculated using Equation 5:

$$R_{FT}^2 = 100 \times \left\{1 - \frac{\sum \hat{e}^2}{\sum (f-\bar{f})^2}\right\},\ \hat{e} = f - (4 \times \hat{y} + 1)^{0.5}, \text{ and } f = y^{0.5} + (y+1)^{0.5} \qquad \text{[Eq. 5]}$$

where y = observed crash frequency and $\hat{y}$=predicted crash frequency.

A calibration factor does not affect the curve shape of an SPF, and this can be shown in Equation 6:

$$\begin{aligned}&Calibrated\ Predicted\ crash\ frequency\ per\ year\\ &= C \times e^{\alpha} \times AADT^{\beta_1} \times Segment\ Length\\ &= e^{\alpha + lnC} \times AADT^{\beta_1} \times Segment\ Length\end{aligned} \qquad \text{[Eq. 6]}$$

where C = calibration factor.

The curve shape of the SPF is governed by the slope coefficient, β_1, and the calibration factor, C, is added to the intercept, α, after being log-transformed. Thus, the calibration factor only shrinks or enlarges the SPF curve vertically without changing the curve shape.

Table 2. Statewide Safety Performance Functions for Multilane Highway and Freeway Segments (Total Crashes)

Site Subtype Code	Site Subtype Description	State	Correlation Structure[a]	α	β_1	d	R_{FT}^2 [b]	Total No. of Sites	Total Length of Sites (mi)	Max. AADT
102	Rural multilane undivided highway segments	VA	UN	-6.91	0.82	0.81	32.5	850	168	39,520
103	Rural multilane divided highway segments		AR	-7.47	0.88	0.46	42.4	4,689	1,531	55,026
104	Rural freeway segments—4 lanes		CS	-6.75	0.80	0.19	64.0	639	1088	36,638
105	Rural freeway segments—6+ lanes		IN	-12.65	1.36	0.27	70.5	44	89	58,820
106	Rural freeway segments within an interchange area—4 lanes		UN	-7.56	0.93	0.50	12.2	369	113	36,638
107	Rural freeway segments within an interchange area—6+ lanes		IN	-13.11*	1.45	0.39	24.4	22	6	58,820
152	Urban multilane undivided arterial segments		CS	-7.88	0.94	5.30	4.6	4,280	508	71,444
153	Urban multilane divided arterial segments		IN	-9.14	1.07	3.92	10.6	10,416	1,448	113,552
155	Urban freeway segments—4 lanes		AR	-18.05	1.98	0.65	37.5	362	254	74,102
156	Urban freeway segments—6 lanes		CS	-12.85	1.45	0.59	51.9	403	233	97,868
157	Urban freeway segments—8+ lanes		CS	-2.17*	0.48	0.58	25.9	207	104	100,735
158	Urban freeway segments within an interchange area—4 lanes		IN	-12.05	1.43	0.85	21.9	326	73	88,893
159	Urban freeway segments within an interchange area—6 lanes		IN	-11.87	1.40	0.64	44.9	369	90	97,868
160	Urban freeway segments within an interchange area—8+ lanes		IN	-13.59	1.54	0.53	10.5	164	37	102,973
102	Rural multilane undivided highway segments	NC	CS	-3.17	0.49	0.53	46.5	NA[c]	308	42,638
103	Rural multilane divided highway segments	MN		-5.05	0.66	0.32	49.8		467	31,188
104	Rural freeway segments—4 lanes	MN		-6.82	0.81	0.17	88.0		379	60,621
105	Rural freeway segments—6+ lanes	CA		-8.28	0.94	0.09	84.3		201	190,403
106	Rural freeway segments within an interchange area—4 lanes	MN		-7.76	0.97	0.15	65.0		90	60,621
107	Rural freeway segments within an interchange area—6+ lanes	CA		-9.63	1.06	0.21	46.1		238	197,798
152	Urban multilane undivided arterial segments	WA		-10.24	1.29	0.85	23.5		194	57,901
153	Urban multilane divided arterial segments	OH		-11.85	1.34	5.91	1.4		327	77,735
155	Urban freeway segments—4 lanes	WA		-7.85	1.00	0.99	9.2		126	151,038
156	Urban freeway segments—6 lanes	WA		-5.96	0.78	0.48	53.5		35	241,255
157	Urban freeway segments—8+ lanes	WA		-16.24	1.67	0.45	43.1		15	223,088
158	Urban freeway segments within an interchange area—4 lanes	WA		-11.23	1.30	0.81	40.9		156	241,255
159	Urban freeway segments within an interchange area—6 lanes	WA		-11.25	1.28	0.60	56.1		83	255,154
160	Urban freeway segments within an interchange area—8+ lanes	WA		-26.76	2.58	0.52	51.6		31	233,323

Equations 3 (freeways) and 4 (multilane highways) should be used for Virginia SPFs. Max. = maximum; AADT = annual average daily traffic (vehicles per day).
For freeways, the AADT and predicted crash frequency for Virginia are for one direction whereas those for the other states are for two directions.

[a] Correlation structure specified for each model: AR = autoregressive order 1; CS = compound symmetry (also known as exchangeable); IN = independent; and UN = unstructured (see Appendix A).

[b] Freeman-Tukey R^2.

[c] Not available.

* Statistically not significant at the 0.05 level.

Table 3. Statewide Safety Performance Functions for Multilane Highway and Freeway Segments (Fatal and Injury Crashes)

Site Subtype Code	Site Subtype Description	State	Correlation Structure[a]	α	β_1	d	R_{FT}^{2}[b]	Total No. of Sites	Total Length of Sites (mi)	Max. AADT
102	Rural multilane undivided highway segments	VA	UN	-8.03	0.84	0.00	21.2	850	168	39,520
103	Rural multilane divided highway segments		AR	-8.05	0.84	0.50	27.5	4,689	1,531	55,026
104	Rural freeway segments—4 lanes		UN	-6.89	0.70	0.16	48.9	639	1,088	36,638
105	Rural freeway segments—6+ lanes		IN	-7.13	0.72	0.14	62.2	44	89	58,820
106	Rural freeway segments within an interchange area—4 lanes		UN	-8.01	0.86	0.44	3.7	369	113	36,638
107	Rural freeway segments within an interchange area—6+ lanes		IN	-11.87*	1.22*	0.30	11.7	22	6	58,820
152	Urban multilane undivided arterial segments		CS	-10.36	1.09	4.25	4.5	4,280	508	71,444
153	Urban multilane divided arterial segments		IN	-10.19	1.06	3.40	9.2	10,416	1,448	113,552
155	Urban freeway segments—4 lanes		IN	-18.27	1.88	0.53	35.2	362	254	74,102
156	Urban freeway segments—6 lanes		IN	-15.64	1.60	0.47	45.6	403	233	97,868
157	Urban freeway segments—8+ lanes		AR	-5.94	0.71	0.50	32.2	207	104	100,735
158	Urban freeway segments within an interchange area—4 lanes		UN	-12.53	1.35	0.74	20.6	326	73	88,893
159	Urban freeway segments within an interchange area—6 lanes		AR	-12.44	1.34	0.64	38.8	369	90	97,868
160	Urban freeway segments within an interchange area—8+ lanes		AR	-12.74	1.37	0.46	14.1	164	37	102,973
102	Rural multilane undivided highway segments	NC	CS	-4.20	0.50	0.53	45.9	NA[c]	308	42,638
103	Rural multilane divided highway segments	MN		-7.46	0.72	0.09	37.2		467	31,188
104	Rural freeway segments—4 lanes	MN		-8.82	0.89	0.16	82.2		379	60,621
105	Rural freeway segments—6+ lanes	CA		-10.25	1.03	0.09	82.8		201	190,403
106	Rural freeway segments within an interchange area—4 lanes	MN		-8.86	0.96	0.24	53.1		90	60,621
107	Rural freeway segments within an interchange area—6+ lanes	CA		-10.48	1.04	0.20	45.3		238	197,798
152	Urban multilane undivided arterial segments	WA		-12.07	1.39	0.81	25.8		194	57,901
153	Urban multilane divided arterial segments	OH		-14.87	1.52	5.81	2.2		327	77,735
155	Urban freeway segments—4 lanes	WA		-8.82	1.02	1.15	12.8		126	151,038
156	Urban freeway segments—6 lanes	WA		-7.60	0.85	0.54	46.4		35	241,255
157	Urban freeway segments—8+ lanes	WA		-19.16	1.85	0.52	39.9		15	223,088
158	Urban freeway segments within an interchange area—4 lanes	WA		-12.89	1.38	0.79	38.1		156	241,255
159	Urban freeway segments within an interchange area—6 lanes	WA		-13.62	1.42	0.55	56.0		83	255,154
160	Urban freeway segments within an interchange area—8+ lanes	WA		-25.63	2.42	0.53	48.9		31	233,323

Equations 3 (freeways) and 4 (multilane highways) should be used for Virginia SPFs. Max. = maximum; AADT = annual average daily traffic (vehicles per day). For freeways, the AADT and predicted crash frequency for Virginia are for one direction whereas those for the other states are for two directions.

[a] Correlation structure specified for each model: AR = autoregressive order 1; CS = compound symmetry (also known as exchangeable); IN = independent; and UN = unstructured (see Appendix A).

[b] Freeman-Tukey R^2.

[c] Not available.

* Statistically not significant at the 0.05 level.

Since the calibration factors only shrink or enlarge the default SPFs vertically without changing the curve shapes of the SPFs, the default SPFs even after being adjusted by the calibration factors are expected to be considerably different from Virginia SPFs in some subtypes such as urban freeway segments outside an interchange area. For example, Figure 3 shows a case of urban freeway segments—8+ lanes. The SPF shapes of Virginia and Washington (default) are notably different. For a fair comparison between Virginia and default SPFs, the default SPF should be calibrated using Virginia data.

A calibration factor adjusting the default SPF to Virginia conditions was calculated. Before the calculation, a multiplication factor was calculated to convert the two-direction default SPF to a one-direction SPF applicable to Virginia data and it was $exp(0.20) = 1.22$. The default SPF for two directions was converted for one direction by multiplying the default SPF by the conversion factor of 1.22. Using the converted default SPF, the calibration factor was calculated to be $exp(1.932) = 2.36$. The curve labeled "Virginia (Calibrated Default)" in Figure 3 represents the calibrated converted default SPF that was created by multiplying the converted default SPF by the calibration factor of 2.36. When compared with the Virginia SPF, the calibrated default SPF underpredicted crash frequencies at AADTs less than about 45,000 and overpredicted at AADTs more than about 45,000.

If the calibrated default SPF were used in selecting potential sites for safety improvement in Virginia, high crash-risk urban freeway segments with 8+ lanes carrying more than 45,000 AADT would likely not be selected whereas low-to-medium crash-risk segments carrying less than 45,000 AADT would likely be selected for safety improvement. This means that customizing SPFs by calibration factors will not be satisfactory from the standpoint of predicting crash frequencies in Virginia for some subtypes. Since predicting crash frequencies is the most important use of the SPFs in Safety Analyst for Virginia, use of the set of SPFs developed in this study based on Virginia data would be better for implementing Safety Analyst in Virginia than adjustment of the default SPFs through calibration factors.

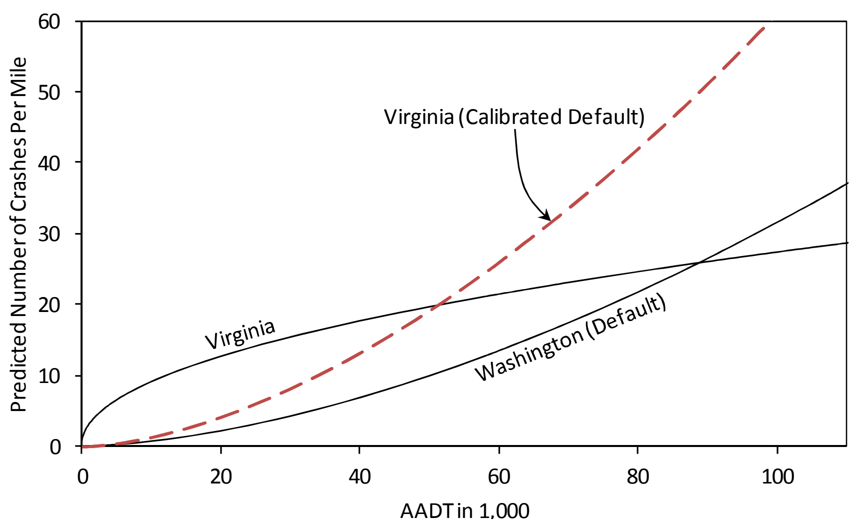


Figure 3. Developed Versus Calibrated Safety Performance Functions of Urban Freeway Segments—8+ Lanes. AADT and predicted crash frequency are for two directions for the default SPF and for one direction for Virginia and the calibrated default SPFs. SPF = safety performance function; AADT = annual average daily traffic (vehicles per day).

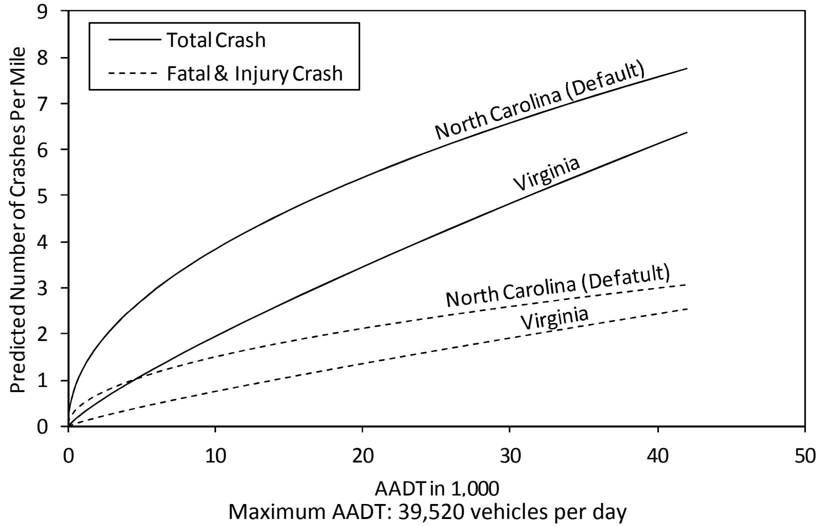
Figures 4 through 7 illustrate the default and Virginia SPFs of Tables 2 and 3 to show the differences between the two sets of SPFs. At a given AADT, crash frequencies predicted by the default SPFs were greater than those predicted by Virginia SPFs for multilane highway segments. The reverse pattern was noted in general for freeway segments. However, the default SPFs shown were not adjusted for Virginia conditions; for freeways, the default SPFs are for two directions whereas the Virginia SPFs are for one direction. Thus, to make a direct comparison between the default and Virginia SPFs, a calibration factor and a conversion factor should be applied. The figures in Appendix C show the Virginia SPFs on scatter plots of observed crash frequencies in Virginia and are helpful in understanding how widely observed crash frequencies are distributed around each SPF curve.

District-Group SPFs

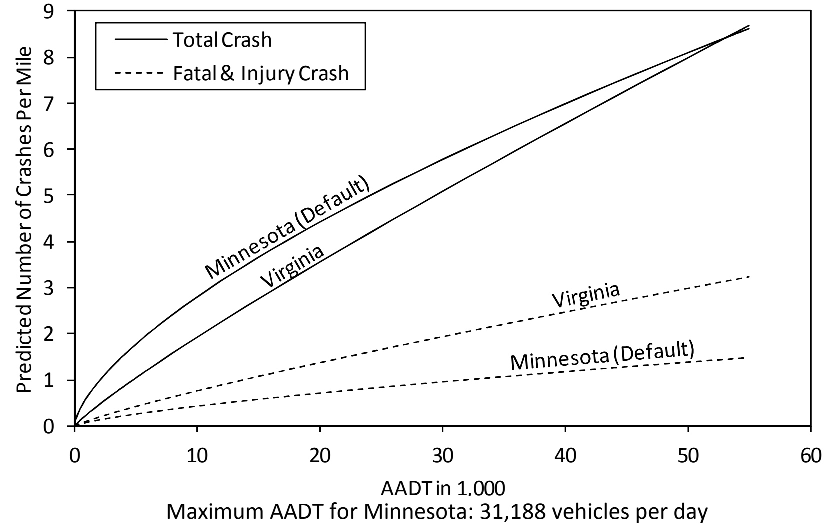
Replacing the default SPFs in Safety Analyst with Virginia SPFs (Tables 2 and 3) will enhance accuracy in predicting crash frequencies. However, as expected, the statewide SPFs will not reflect variation across Virginia. If regional differences are large, customizing SPFs in a way to reflect the variation will further enhance the prediction accuracy. Reflecting the variation is possible by creating new subtypes in Safety Analyst. For example, when a state can be divided into two regions, eastern and western, where driving environments and behaviors related to traffic safety are different, "region" subtypes can be created and permutated with the existing subtypes. In the case of multilane highway segments, a total of eight subtypes can be defined: urban/rural divided/undivided eastern/western subtypes. Then, a separate SPF can be developed for each of the eight subtypes.

In Virginia, districts have been frequently tied with variations across the state from a traffic safety perspective and are considered to be the most efficient unit for data preparation from a viewpoint of implementing Safety Analyst. Thus, a district can serve as a geographical base unit for exploring new subtypes that can reflect variations across the state. However, creating too many new subtypes should be discouraged because it will greatly complicate implementation of Safety Analyst, and therefore opportunities to combine several districts together should be explored. To explore appropriate ways of grouping districts, a comparative analysis was performed using total crash SPFs for multilane highways.

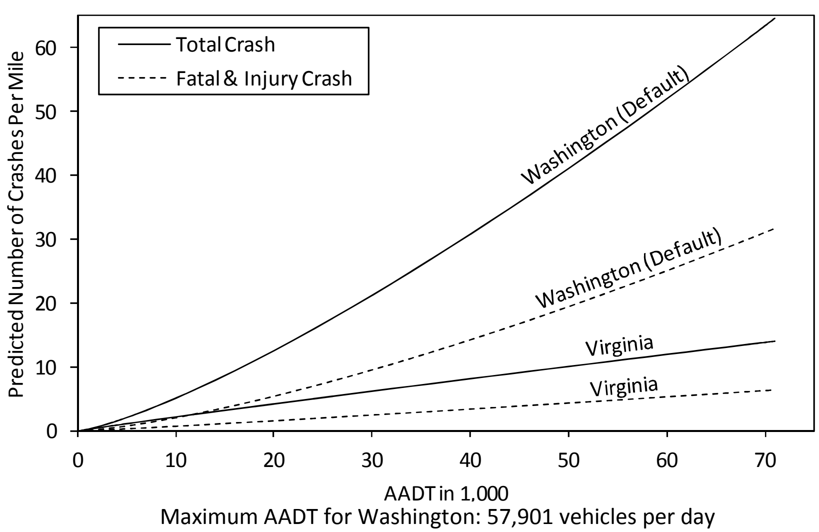
For each of the four existing subtypes in multilane highway segments, district-specific SPFs were first developed, resulting in nine separate SPFs. The coefficient estimates of the nine SPFs were then statistically compared to determine which coefficients could be combined together based on Welch's *t*-test with the 0.05 significance level. Through an iterative process of comparing and merging districts, the final grouping schemes were generated. The final SPFs estimated following the final grouping schemes are presented in Table 4 by VDOT district. When two districts belong to the same group, the coefficients of these districts are identical in Table 4. For example, for rural undivided segments, the coefficients for Districts 2, 3, 4, 8, and 9 (Salem, Lynchburg, Richmond, Staunton, and Northern Virginia, respectively) were found to be statistically identical; thus, these districts were combined to form one group. Although their coefficients are presented in separate rows in Table 4, their values are identical.



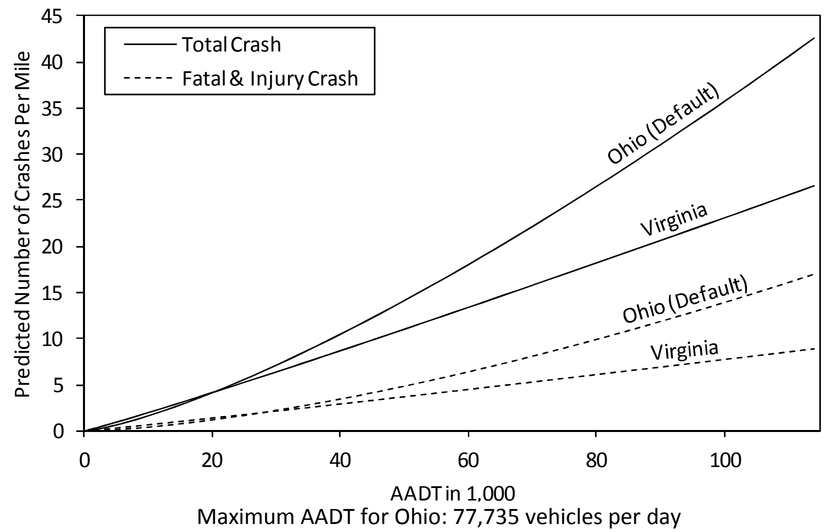
(a) Rural undivided segments



(b) Rural divided segments

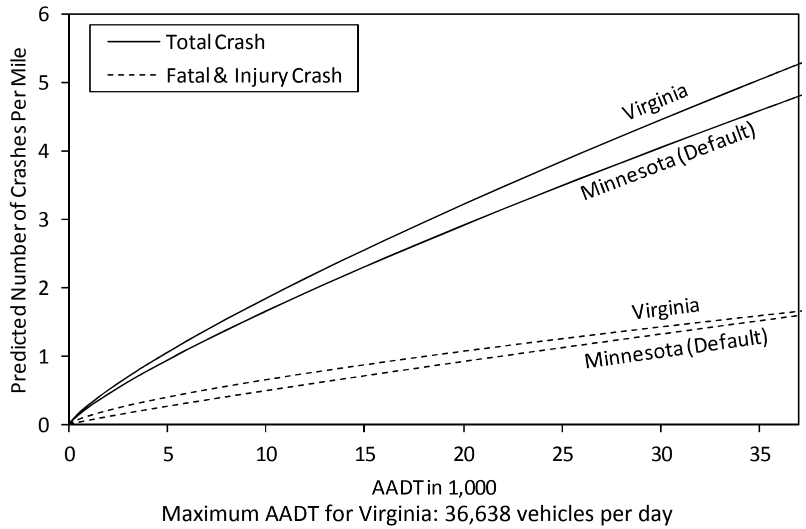


(c) Urban undivided segments

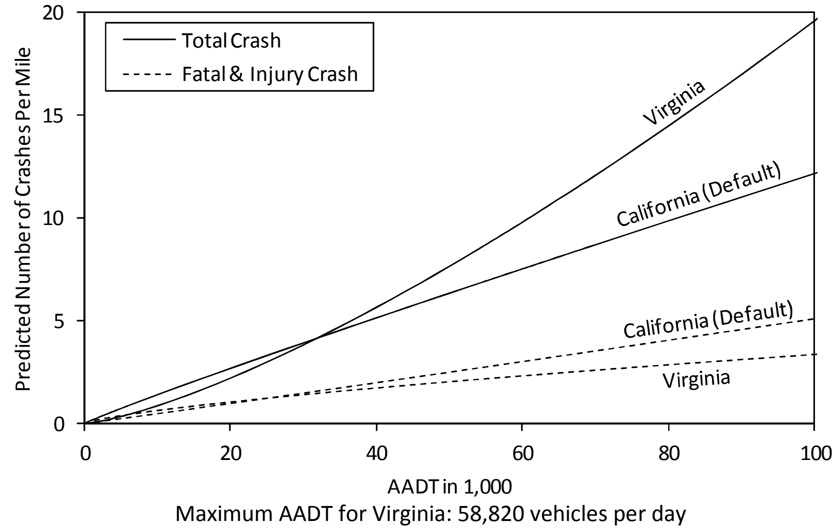


(d) Urban divided segments

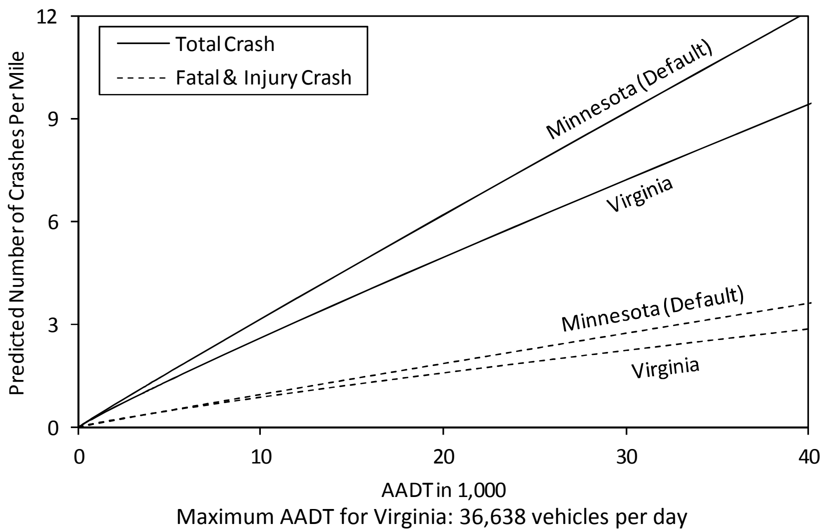
Figure 4. Statewide Safety Performance Functions of Multilane Highways in Virginia and Other States. AADT and predicted crash frequency are for two directions combined. AADT = annual average daily traffic (vehicles per day).



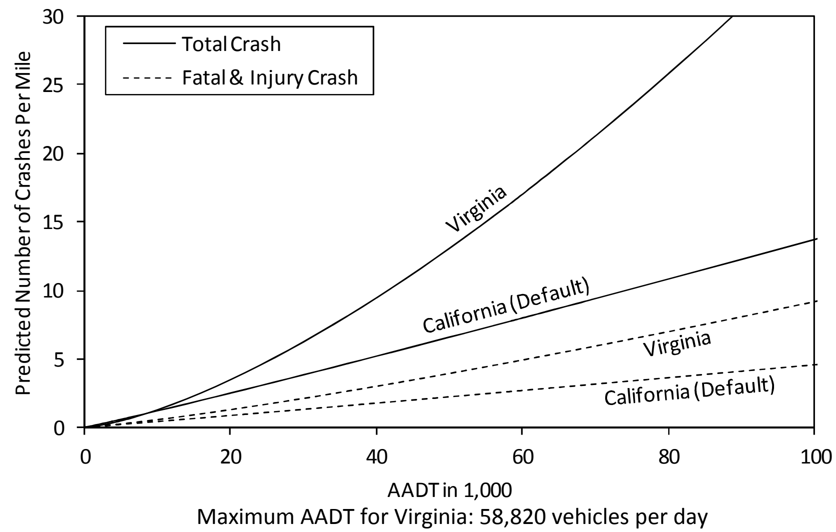
(a) Segments—4 lanes



(b) Segments—6+ lanes

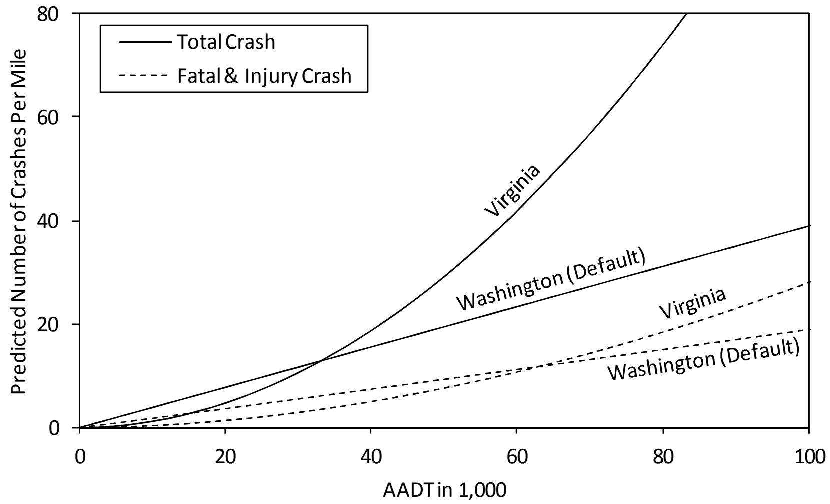


(c) Segments within an interchange area—4 lanes



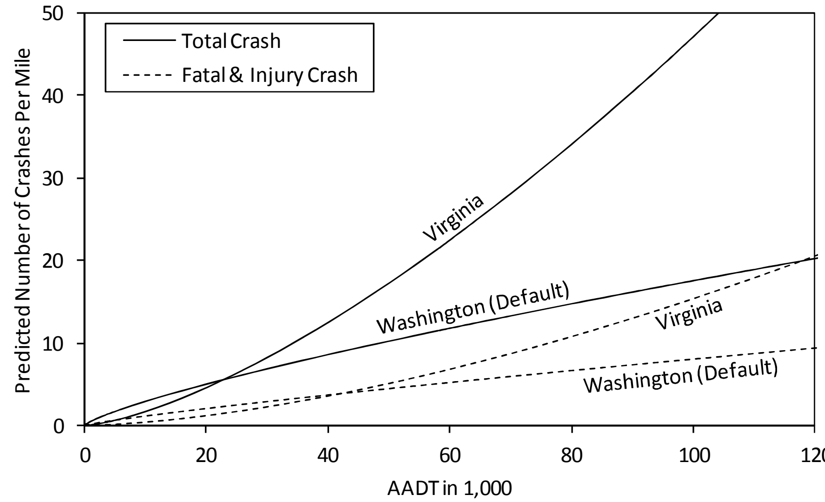
(d) Segments within an interchange area—6+ lanes

Figure 5. Statewide Safety Performance Functions of Rural Freeways in Virginia and Other States. AADT and predicted crash frequency are for two directions for default SPFs and for one direction for Virginia SPFs. AADT = annual average daily traffic (vehicles per day).



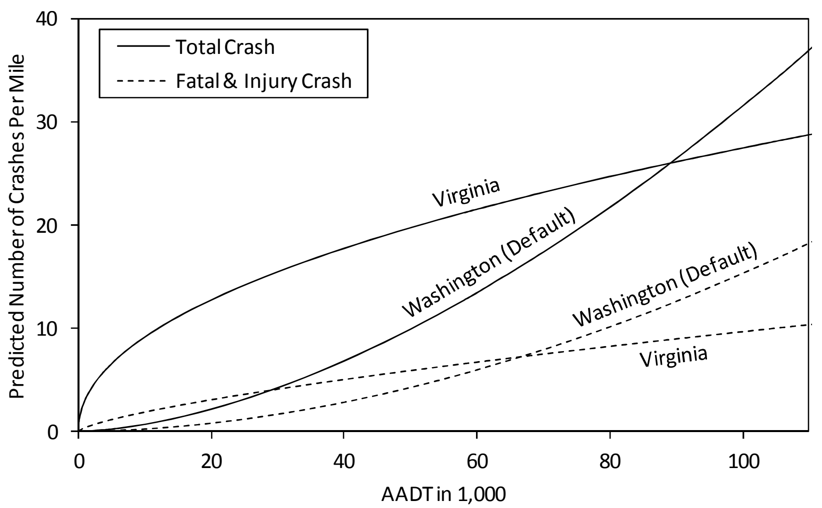
Maximum AADT for Virginia: 74,102 vehicles per day

(a) Segments—4 lanes



Maximum AADT for Virginia: 97,868 vehicles per day

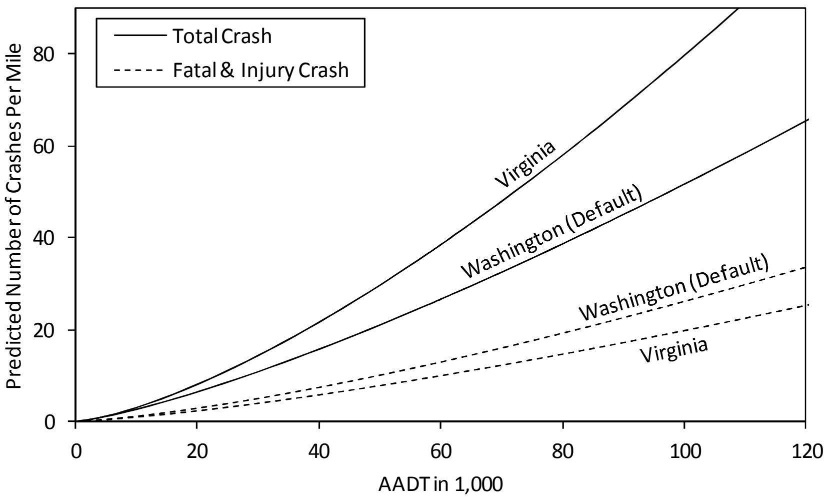
(b) Segments—6 lanes



Maximum AADT for Virginia: 100,735 vehicles per day

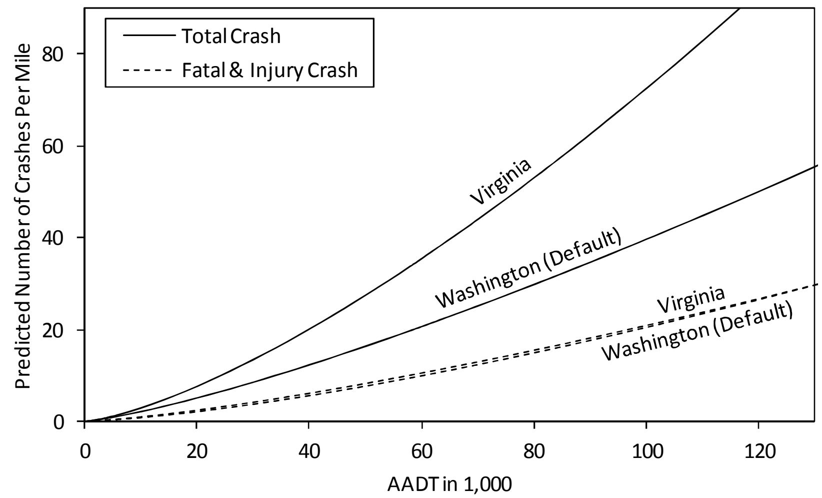
(c) Segments—8+ lanes

Figure 6. Statewide Safety Performance Functions of Urban Freeways Outside an Interchange Area in Virginia and Other States. AADT and predicted crash frequency are for two directions for default SPFs and for one direction for Virginia SPFs. AADT = annual average daily traffic (vehicles per day).



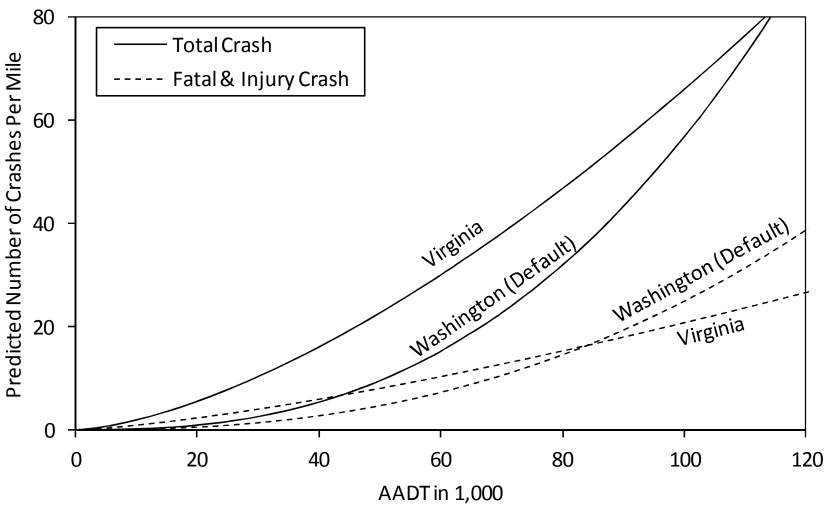
Maximum AADT for Virginia: 88,893 vehicles per day

(a) Segments within an interchange area—4 lanes



Maximum AADT for Virginia: 97,868 vehicles per day

(b) Segments within an interchange area—6 lanes



Maximum AADT for Virginia: 102,973 vehicles per day

(c) Segments within an interchange area—8+ lanes

Figure 7. Statewide Safety Performance Functions of Urban Freeways Within an Interchange Area in Virginia and Other States. AADT and predicted crash frequency are for two directions for default SPFs and for one direction for Virginia SPFs. AADT = annual average daily traffic (vehicles per day).

Table 4. VDOT District-Group Safety Performance Functions of Multilane Highway Segments in Virginia (Total Crashes)

Site Subtype Code	Site Subtype Description	District	Correlation Structure[a]	α	β_1	d	$R_{FT}^{2\,b}$	Total No. of Sites	Total Length of Sites (mi)	Max. AADT
102	Rural multilane undivided highway segments	1 (Bristol)	UN	0.00	0.09	0.64	35.5	56	7	18,821
		2 (Salem)		-7.03	0.83			173	29	28,540
		3 (Lynchburg)		-7.03	0.83			45	5	18,004
		4 (Richmond)		-7.03	0.83			83	19	16,495
		5 (Hampton Roads)		-16.86	1.86			167	46	28,748
		6 (Fredericksburg)		-4.49	0.57			170	34	23,036
		7 (Culpeper)		0.00	0.00			25	2	39,520
		8 (Staunton)		-7.03	0.83			121	22	27,657
		9 (Northern Virginia)		-7.03	0.83			10	2	6,374
103	Rural multilane divided highway segments	1 (Bristol)	AR	-6.14	0.74	0.45	42.7	641	218	23,945
		2 (Salem)		-6.14	0.74			814	192	28,540
		3 (Lynchburg)		-7.82	0.92			560	233	21,991
		4 (Richmond)		-6.14	0.74			548	196	42,505
		5 (Hampton Roads)		-10.08	1.15			450	159	26,640
		6 (Fredericksburg)		-10.08	1.15			571	217	43,748
		7 (Culpeper)		-7.82	0.92			486	154	49,185
		8 (Staunton)		-6.14	0.74			549	141	35,924
		9 (Northern Virginia)		-10.08	1.15			69	22	55,026
152	Urban multilane undivided arterial segments	1 (Bristol)	CS	-23.69	2.54	5.23	5.5	97	11	25,623
		2 (Salem)		0.00	0.10			417	47	27,124
		3 (Lynchburg)		-10.97	1.27			321	33	35,117
		4 (Richmond)		-10.97	1.27			650	74	47,057
		5 (Hampton Roads)		-6.89	0.84			1,022	141	71,444
		6 (Fredericksburg)		-10.97	1.27			132	20	56,982
		7 (Culpeper)		-23.69	2.54			34	5	43,236
		8 (Staunton)		-10.97	1.27			147	22	27,657
		9 (Northern Virginia)		-6.89	0.84			1,461	156	64,334
153	Urban multilane divided arterial segments	1 (Bristol)	IN	-10.70	1.22	3.54	16.4	194	29	32,639
		2 (Salem)		-13.76	1.56			770	115	65,081
		3 (Lynchburg)		-10.70	1.22			410	58	51,439
		4 (Richmond)		-13.76	1.56			2,371	313	100,111
		5 (Hampton Roads)		-5.97	0.70			2,774	422	92,201
		6 (Fredericksburg)		-5.97	0.70			233	35	92,399
		7 (Culpeper)		-10.70	1.22			209	28	59,667
		8 (Staunton)		-13.76	1.56			339	50	37,870
		9 (Northern Virginia)		-7.28	0.89			3,115	400	113,552

Equation 4 should be used for multilane highway segment SPFs. Max. = maximum; AADT = annual average daily traffic (vehicles per day).
[a] Correlation structure specified for each model: AR = autoregressive order 1; CS = compound symmetry (also known as exchangeable); IN = independent; and UN = unstructured
[b] Freeman-Tukey R^2.

It should be noted that an SPF for each district-group was not obtained from a separate estimation of an SPF for each group but was rearranged after a single SPF containing all statistically significant differential coefficients across the groups was estimated. For example, for rural undivided segments, Districts 2, 3, 4, 8, and 9 (Salem, Lynchburg, Richmond, Staunton, and Northern Virginia, respectively) were combined to form a group and one set of coefficient estimates was obtained for the group so that the estimates were identical for all five districts in the group. Then, a separate SPF for each of the five districts was written using the estimates, resulting in five identical SPFs, one for each district. This is why one estimate of the dispersion parameter (*d*) and one R_{FT}^2 value are reported for each subtype in Table 4 and different estimates of coefficients (*a* and b_1) varying across districts are found. The correlation structures found to perform the best for the statewide SPFs (Table 2) were retained.

Figure 8 shows the district-group SPFs for rural multilane highways and their corresponding statewide SPFs. There are three district groups for rural segments and four for urban segments. The number of districts in one group varies from one (e.g., District 6 [Fredericksburg] for rural undivided segments) to five (e.g., Districts 2, 3, 4, 8, and 9 [Salem, Lynchburg, Richmond, Staunton, and Northern Virginia, respectively] for rural undivided segments). Although some district-group SPFs look drastically different from the rest of the district-group SPFs, the actual ranges of AADTs should be considered. For example, for rural undivided segments, the SPF for District 5 (Hampton Roads) (not combined with any other district) looks very different from the SPFs of the other district-groups. However, the maximum AADT on rural undivided segments in District 5 (Hampton Roads) was 28,748 vehicles per day. This means that although the curve of District 5 (Hampton Roads) can run well beyond 30,000 AADT, using the curve (i.e., SPF) for predicting crash frequencies for conditions above 30,000 AADT would be inappropriate.

The number of segments and total length of those segments should also be considered when the district-group SPFs are applied. For example, for rural undivided segments, District 1 (Bristol) formed a separate group by itself. However, there are only 56 rural undivided segments totaling 7 miles in District 1 (Bristol). The curves constructed from this relatively small sample size could be substantially impacted by the addition of segments with crash characteristics that were different from those of the original segments.

As seen in Figure 8, the number and composition of district-groups were not consistent across the four subtypes. Some consistency was found such as District 1 (Bristol) being separated from Districts 5, 6, and 9 (Hampton Roads, Fredericksburg, and Northern Virginia, respectively) in all four subtypes, but general rules for grouping districts could not be developed. To create new subtypes based on the district-groups, different numbers and definitions of new subtypes varying across the four existing subtypes should be created. For example, four new subtypes would be created for rural undivided segments, the first containing District 5 (Hampton Roads); the second containing Districts 2, 3, 4, 8, and 9 (Salem, Lynchburg, Richmond, Staunton, and Northern Virginia, respectively); the third containing District 6 (Fredericksburg); and the fourth containing District 1 (Bristol). Three new subtypes would be created for rural divided segments, the first containing Districts 5, 6, and 9 (Hampton Roads, Fredericksburg, and Northern Virginia, respectively); the second containing Districts 3 and 7 (Lynchburg and Culpeper, respectively); and the third containing Districts 1, 2, 4, and 8 (Bristol, Salem, Richmond, and Staunton, respectively). This lack of general consistency in district-grouping results causes difficulty in incorporating the developed district-group SPFs into Safety Analyst. Thus, it seems practically reasonable to implement Safety Analyst with the statewide SPFs for multilane highway segments. For freeways, the district-grouping approach was not considered because not all districts had freeway routes.

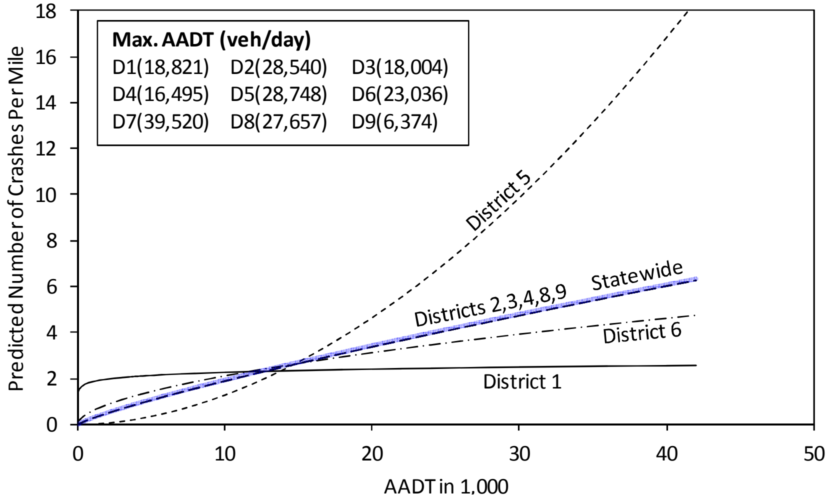
Implementation Aspects of Freeway Segment SPFs in Safety Analyst

VDOT's RNS maintains freeway segment data directionally, as separate sites. This is also true for a small portion of multilane highways. Meanwhile, procedures of Safety Analyst such as those applying SPFs and the empirical Bayes method are basically designed for both directions combined. To accommodate two different practices in recording directional segments across the United States, Safety Analyst provides separate ways for the two practices: (1) treating the separate directions of travel as separate sites (corresponding to the one-way operation data element) and (2) treating the separate directions as the same site (corresponding to the two-way operation data element (AASHTO, 2013b).

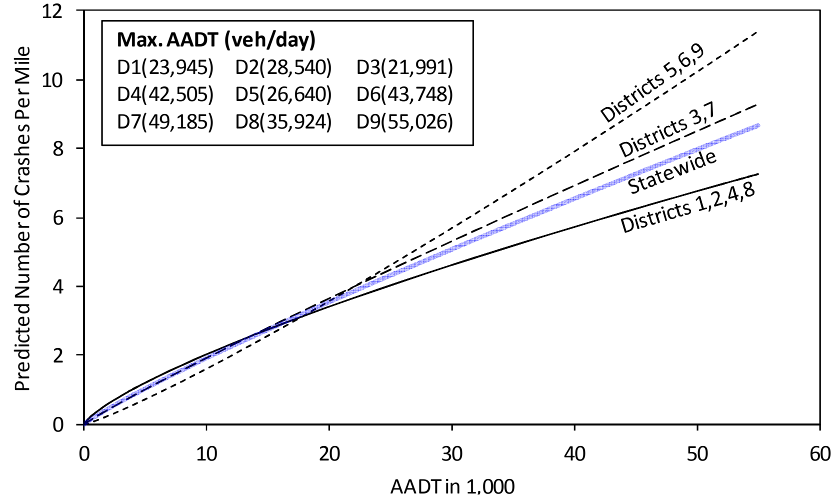
However, the two ways that Safety Analyst currently provides do not seem suitable for RNS without modification since they seem to require a database structure matching separate directions on the same segment; the freeway segments in RNS are currently not aligned in such a manner. To satisfy such a matching structure, a new roadway inventory table needs to be created for freeway segments. The new table can be created for treating the separate directions as either (1) separate sites or (2) the same site. The former would record the combined AADT and crash frequency of the two directions, and the latter would record the directional AADT and crash frequency with Safety Analyst summing the two directions internally. A table created from the latter approach would need a segment identifier where the separate directions of the same segment have the same value while being in separate records.

CONCLUSIONS

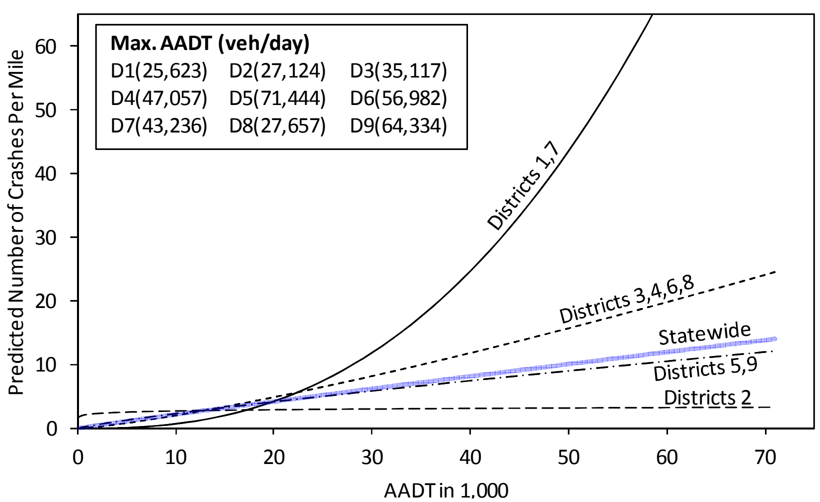
- *Default SPFs in Safety Analyst are different from the Virginia SPFs for multilane highway and freeway segments developed in this study*. The curve shapes of the default SPFs were not well matched with the Virginia statewide SPFs developed using local data. This means that the default SPFs do not properly represent the relationships between annual crash frequencies and AADT on such segments in Virginia. If calibration factors adjusting the default SPFs to Virginia conditions were applied, the adjusted default SPFs would be matched with the Virginia SPFs for conditions with average AADT levels but would either overpredict or underpredict crash frequencies at low or high AADTs. The extent of the overprediction or underprediction would vary by subtype.



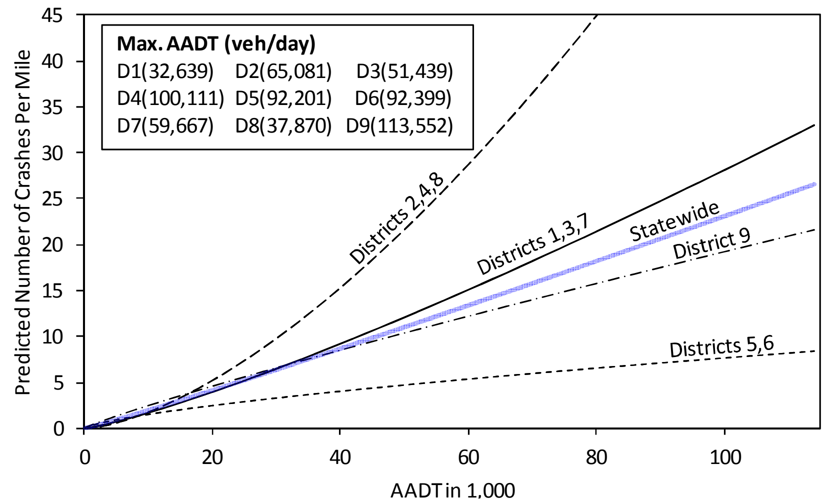
(a) **Rural undivided segments**



(b) **Rural divided segments**



(c) **Urban undivided segments**



(d) **Urban divided segments**

Figure 8. VDOT District-Group Safety Performance Functions of Multilane Highways in Virginia (Total Crashes). A safety performance function (SPF) curve of a district is valid within the maximum AADT indicated for the district. An SPF for District 7 on rural undivided segments is not presented in (a) because it was not statistically significant. AADT = annual average daily traffic (vehicles per day); District 1 (Bristol); District 2 (Salem); District 3 (Lynchburg); District 4 (Richmond); District 5 (Hampton Roads); District 6 (Fredericksburg); District 7 (Culpeper); District 8 (Staunton); District 9 (Northern Virginia).

- *Sizable variations in the curve shapes of the Virginia SPFs for multilane highway segments exist across Virginia*. District-group SPFs developed using the VDOT district-based data revealed that the shapes of the Virginia SPFs vary across VDOT's districts on multilane highway segments and the level of variations varies by subtype.

- *Creating new subtypes based on VDOT district-groups resulting from this study for multilane highway segments is not suitable for the current version of Safety Analyst*. According to the district-group SPFs developed using Virginia data, the number and composition of district-groups vary by existing subtype of multilane highway segments. The lack of consistency in grouping districts in this facility type cannot be accommodated in the current version of Safety Analyst.

- *Modifications to RNS are needed to support the implementation of freeway segment SPFs in Safety Analyst.* VDOT's practice of maintaining roadway inventory data for freeway segments does not appear to fit either of the two data loading approaches that Safety Analyst currently provides. Thus, to implement Virginia freeway segment SPFs in Safety Analyst, either a new inventory table needs to be created or data management of the current table needs to be modified to comply with a database format required for Safety Analyst.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division should use the Virginia statewide SPFs for multilane highway and freeway segments developed in this study for implementing Safety Analyst*. The Virginia statewide SPFs in Tables 2 and 3 are different from the default SPFs embedded in Safety Analyst for these segments. If the default SPFs were adjusted to Virginia conditions by calibration factors, inaccurate prediction of crash frequencies would be expected at low and high AADTs, which was illustrated with urban freeway segments with 8+ lanes (Figure 3).

2. *VDOT's Traffic Engineering Division should use the Virginia statewide or district-group SPFs for multilane highway segments and the statewide SPFs for freeway segments developed in this study when implementation of Safety Analyst is not feasible.* The district-group SPFs for multilane highway segments cannot be implemented in Safety Analyst. However, all SPFs developed in this study including the district-group SPFs are implementable without Safety Analyst. The statewide SPFs adjusted by district-group calibration factors can account for variation across districts to some extent.

BENEFITS AND IMPLEMENTATION PROSPECTS

The Virginia statewide and district-group SPFs developed in this study are expected to be used to identify segments for safety improvement; evaluate the safety conditions of existing and future segments; and quantify the safety effects of changes in the geometric and/or operational features of segments. With the developed statewide SPFs, VDOT will be able to maximize the benefits of implementing Safety Analyst for multilane highway and freeway segments. With the statewide and district-group SPFs, VDOT will also be able to predict crash frequencies for its safety programs. For example, segments on multilane highways and freeways can be prioritized for developing safety improvement projects for the Highway Safety Improvement Program using the predicted crash frequencies.

Recommendation 1 can be implemented by replacing the default SPFs in Safety Analyst with the statewide SPFs developed in this study (Tables 2 and 3). VDOT's Information Technology Division, VDOT's Transportation Engineering Division (TED), and the Virginia Center for Transportation Innovation and Research (VCTIR) may need to work together to implement this recommendation.

Recommendation 2 can be implemented by adopting the developed statewide (Tables 2 and 3) and district-group (Table 4) SPFs in selecting sites for safety improvement programs. VDOT's TED and VCTIR may need to work together to implement this recommendation. VDOT's districts may well be able to use the SPFs for their safety programs, and VDOT's TED and VCTIR can help them use the SPFs in an efficient and correct manner.

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APPENDIX A

ESTIMATION AND EVALUATION OF A PANEL COUNT DATA MODEL

Generalized Estimating Equation

The GEE of Liang and Zeger (1986) is a method of estimating the parameters of a generalized linear model such as a negative binomial model on panel data using a preset correlation structure that would exist in repeated measures of the dependent variable. GEE estimates of the model parameters are known to be consistent even when the correlation structure is misspecified (Diggle et al., 2002). Negative binomial models for SPFs were estimated using GEE by specifying REPEATED statement with TYPE option in PROC GENMOD. Kweon and Lim (2012) used GEE to estimate eight panel negative binomial models for developing intersection SPFs.

Four Correlation Structures

The four correlation structures are (1) independent; (2) compound symmetry, also known as exchangeable; (3) autoregressive; and (4) unstructured correlation structures. All structures except for the independent structure assume that the annual crash frequencies are correlated over the 5 years but in different ways, as shown here.

Independent (IN):
$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Compound Symmetry (CS):
$$\begin{bmatrix} 1 & \rho & \rho & \rho & \rho \\ \rho & 1 & \rho & \rho & \rho \\ \rho & \rho & 1 & \rho & \rho \\ \rho & \rho & \rho & 1 & \rho \\ \rho & \rho & \rho & \rho & 1 \end{bmatrix}$$

Autoregressive (AR):
$$\begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 & \rho^4 \\ \rho & 1 & \rho & \rho^2 & \rho^3 \\ \rho^2 & \rho & 1 & \rho & \rho^2 \\ \rho^3 & \rho^2 & \rho & 1 & \rho \\ \rho^4 & \rho^3 & \rho^2 & \rho & 1 \end{bmatrix}$$

Unstructured (UN):
$$\begin{bmatrix} 1 & \rho_{21} & \rho_{31} & \rho_{41} & \rho_{51} \\ \rho_{21} & 1 & \rho_{32} & \rho_{42} & \rho_{52} \\ \rho_{31} & \rho_{32} & 1 & \rho_{43} & \rho_{53} \\ \rho_{41} & \rho_{42} & \rho_{43} & 1 & \rho_{54} \\ \rho_{51} & \rho_{52} & \rho_{53} & \rho_{54} & 1 \end{bmatrix}$$

The independent structure assumes no correlation over the 5 years. The negative binomial regression ignoring a panel data structure (i.e., omitting REPEATED statement in PROC GENMOD) is identical to the regression with the independent structure in coefficient estimates yet different in standard error estimates. The compound symmetry structure assumes an identical correlation between any two different years, whereas the autoregressive structure assumes that a correlation between two years diminishes as the two years become further away. Both correlations require an estimation of only one correlation parameter. The unstructured structure assumes a different correlation for any two different years, which is the most complex structure, and requires 10 correlation coefficients to be estimated for 5-year data. Further details are provided by Kweon and Lim (2012).

Quasi-likelihood Information Criterion

Akaike's information criterion (AIC), proposed by Akaike (1974), is one of the most popular criterion for model performance comparison and is based on likelihoods. However, it is not applicable to models estimated by GEE because GEE is not based on likelihoods. QIC, proposed by Pan (2001), is a modified version of AIC suitable for models estimated by GEE. A model with a smaller QIC value is viewed as performing better than one with a larger QIC value. Kweon and Lim (2012) used QIC to select the best correlation structure among eight structures for intersection SPFs.

APPENDIX B

NON-PARAMETRIC MODEL AND ESTIMATION RESULTS

Penalized B-Spline Model

A smoothing spline is a piecewise smooth polynomial function with the polynomial pieces connected at knots, and B-spline is a basis spline proposed by de Boor (1978). The penalized B-spline employed in this study is a non-iterative B-spline transformation on explanatory variables and was proposed by Eilers and Marx (1996). A smoothing parameter for the transformation was determined by the Schwarz-Bayesian criterion, and other parameters for fitting the spline were set at default values (e.g., cubic spline with 100 evenly spaced knots and 3 evenly spaced exterior knots). Graphical outputs of the penalized B-spline models are useful in examining how well the SPFs developed in this study are matched with the underlying relationship represented by the resulting B-spline curves.

Modeling Results and Discussions

A penalized B-spline curve was fit to each of the four subtypes of multilane highway segments and the five subtypes of freeway segments. The curves predicting the annual crash frequency per mile are presented in Figures B1 through B3, and their 95th percentile confidence intervals are also presented. The developed statewide SPFs (Tables 2 and 3) are overlaid on the figures for comparison. Because the penalized B-spline curves are deemed to represent an underlying relationship between crash frequency and AADT, the functional form (Eq. 1) of the SPFs can be assessed by a visual comparison of the developed SPFs against the corresponding penalized B-spline curves; the confidence intervals add a statistical perspective to the assessment.

It should be noted that a confidence interval should not be confused with a prediction interval. The *confidence interval* is used to evaluate the uncertainty of an estimate of an *average* crash frequency of all segments carrying a certain AADT, whereas the *prediction interval* is used to evaluate the uncertainly of an estimate of an *individual* crash frequency of a segment carrying a certain AADT. Because the prediction interval takes into account variability in the conditional distribution of an actual crash frequency as well as variability in the estimate of the average crash frequency, it is typically much wider than the confidence interval.

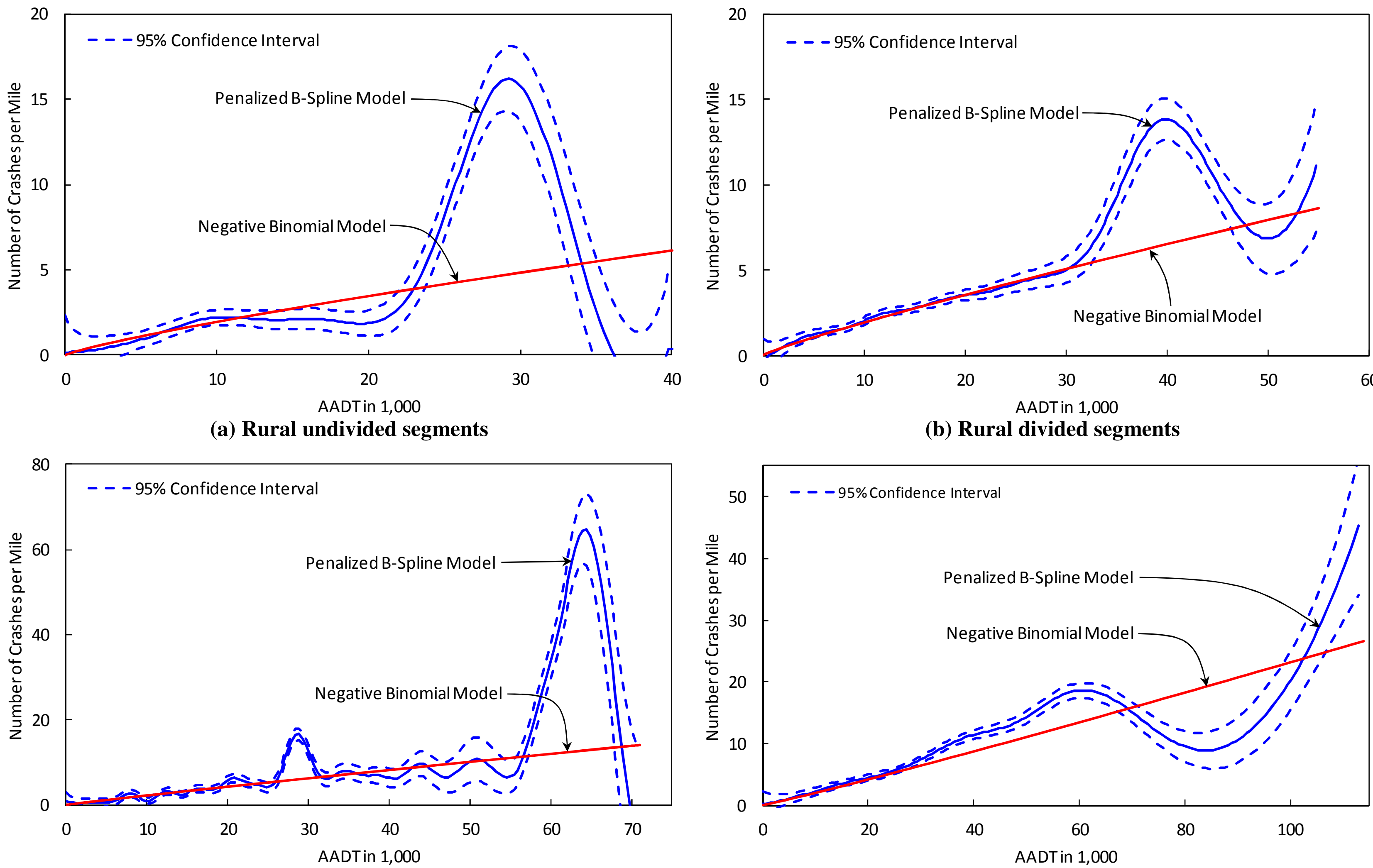
In this study, the estimate of an *average* crash frequency can be called a *state-overall* prediction of an annual crash frequency and an estimate of an *individual* crash frequency can be called a *segment-specific* prediction. The prediction curves (solid lines in the figures) indicate both state-overall and segment-specific predictions of annual crash frequencies corresponding to varying AADTs. However, the uncertainties of these two predictions are different. The confidence intervals (dotted lines in the figures) represent the uncertainty of the *state-overall* predictions, whereas the prediction intervals, not shown here, represent the uncertainty of the *segment-specific* predictions. For the purpose of assessing the functional forms of the developed SPFs (Tables 2 and 3) against the penalized B-spline curves, the confidence intervals are appropriate and the typical 95% confidence level was adopted to construct these intervals. As stated previously, the SPFs were developed using the negative binomial model with the functional form (Eq. 1) required for Safety Analyst.

As for the multilane highways (Figure B1), the B-spline curves are deviated from the developed SPFs for high AADTs. For the example of rural undivided segments, the B-spline curves are considerably higher than the developed SPF for the segments carrying an AADT of around 30,000. As for the freeway segments outside an interchange area (Figures B2 and B3), deviations of the developed SPFs from the B-spline curves are also noticeable at high AADTs but patterns and degrees of deviations are more diverse than those found in the multilane highways. The SPFs for the rural segments with 4 lanes and urban segments with 6 and 8+ lanes are generally in line with the B-spline curves. Those for the rural segments with 6 lanes and the urban segments with 4 lanes appear severely deviated from their corresponding B-spline curves at medium and/or high AADTs.

Deviations of the B-spline curves from the developed SPFs might indicate that some segment characteristics not included in the SPFs might enhance or deteriorate safe driving conditions on the segments, and they are associated with AADTs. For rural undivided segments of multilane highways (Figure B1a), suppose that horizontal curves with inadequate sight distances and driveways are concentrated on segments carrying about 30,000 AADT. These segments would very likely experience more crashes than other segments because such design features are understood to create less safe conditions than segments without such curves and driveways.

The SPFs for Safety Analyst are required to adopt the non-decreasing functional form of Equation 1 (i.e., no decrease in the predicted crash frequency as AADT increases), and the study data do not include information pertaining to such design features. Thus, the required functional form along with the lack of the information would result in Figure B1a showing large differences between the two curves at around 30,000 AADT. Without the information about the design features associated with less safe conditions, the penalized B-spline model can still capture the dramatic increase in crash frequencies at around 30,000 AADT whereas the negative binomial model of an SPF in the required model specifications cannot do so.

The developed SPFs that are not well matched with penalized B-spline curves such as the SPF for rural undivided segments of multilane highways (Figure B1a) are still useful in identifying potential segments for safety improvement. For the hypothetical example with horizontal curves and driveways, a large proportion of rural undivided segments carrying about 30,000 AADT would be identified as potential safety improvement segments if the developed SPF was used for identification and prioritization (see Figure B1a). When further investigation of the identified segments, involving collecting more segment characteristics and field visits, was conducted, it would probably be discovered that horizontal curves and driveways pose unsafe driving conditions on many of the identified segments, which would then lead to selection of appropriate countermeasures.



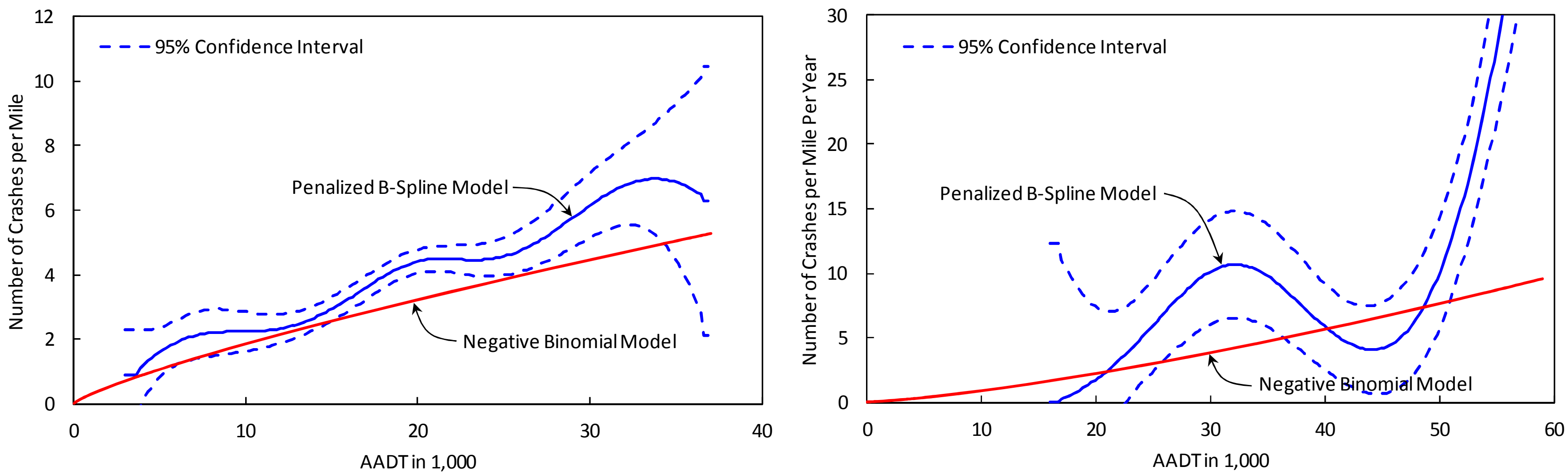
(a) Rural undivided segments

(b) Rural divided segments

(c) Urban undivided segments

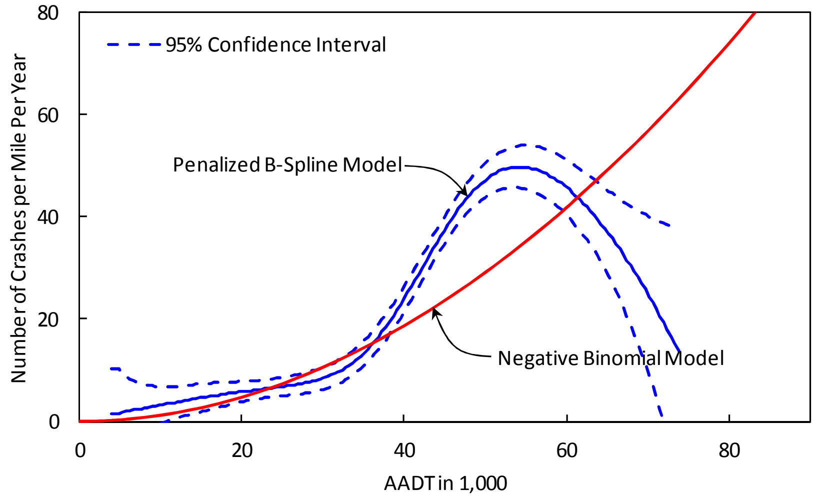
(d) Urban divided segments

Figure B1. Comparison of Functional Forms of Statewide Safety Performance Functions of Multilane Highway Segments in Virginia. AADT = annual average daily traffic (vehicles per day).

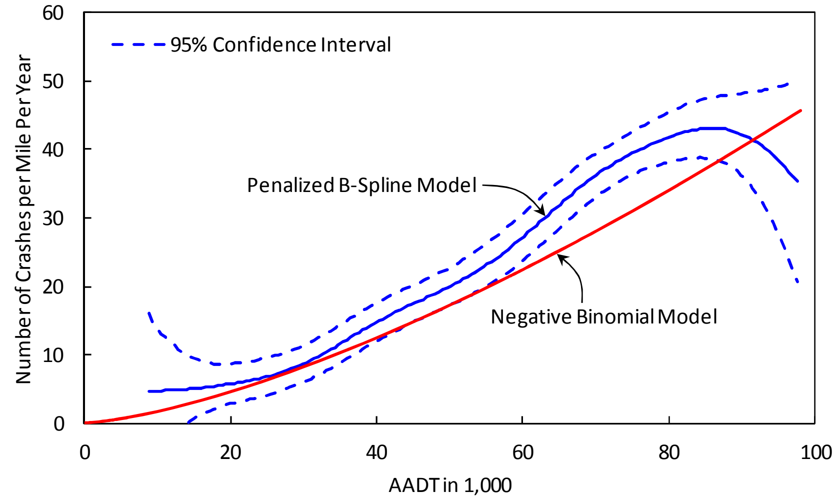


(a) Rural segments (4 lanes) **(b) Rural segments (6 lanes)**

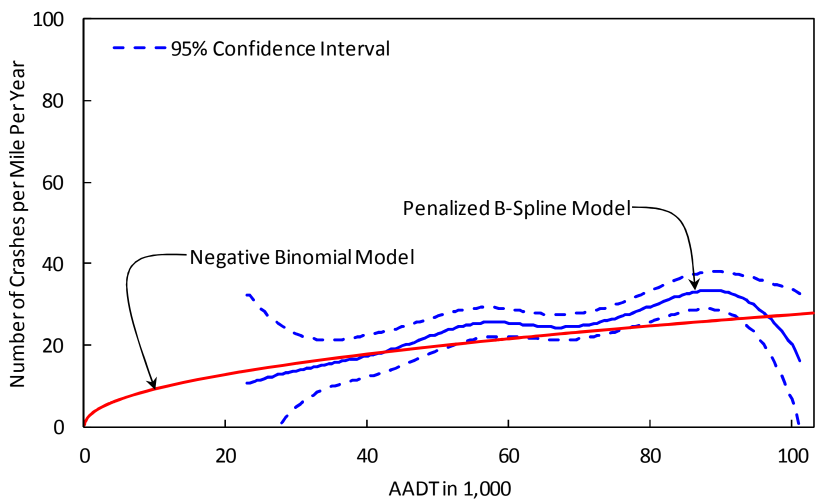
Figure B2. Comparison of Functional Forms of Statewide Safety Performance Functions of Rural Freeways Outside an Interchange Area in Virginia.
AADT = annual average daily traffic (vehicles per day).



(a) Urban segments (4 lanes)



(b) Urban segments (6 lanes)

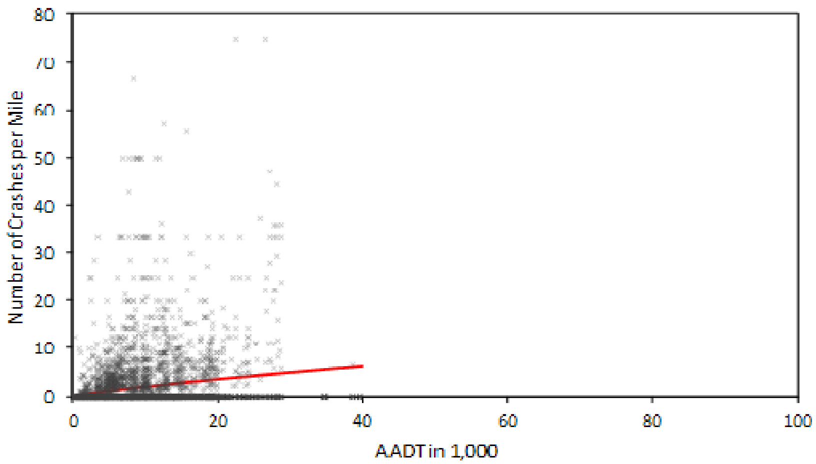


(c) Urban segments (8+ lanes)

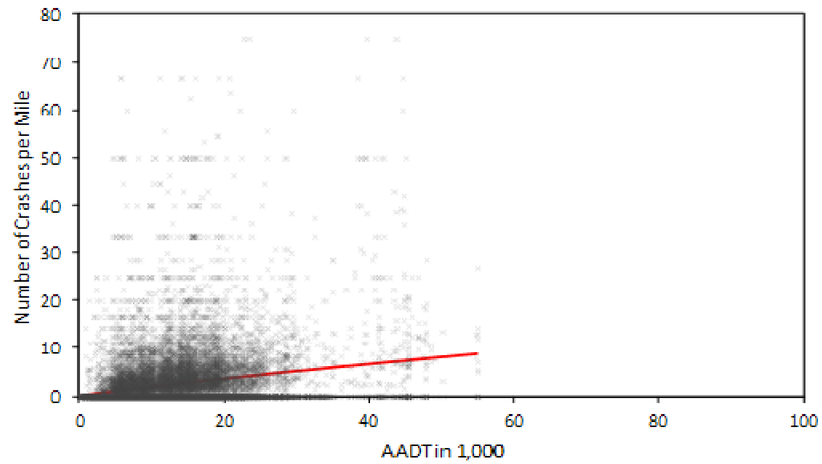
Figure B3. Comparison of Functional Forms of Statewide Safety Performance Functions of Urban Freeways Outside an Interchange Area in Virginia. AADT = annual average daily traffic (vehicles per day).

APPENDIX C

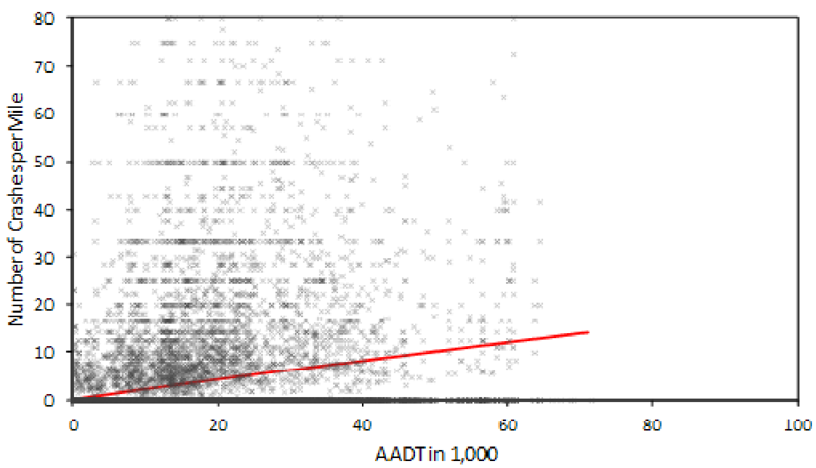
SCATTERPLOTS OF MULTILANE HIGHWAYS IN VIRGINIA



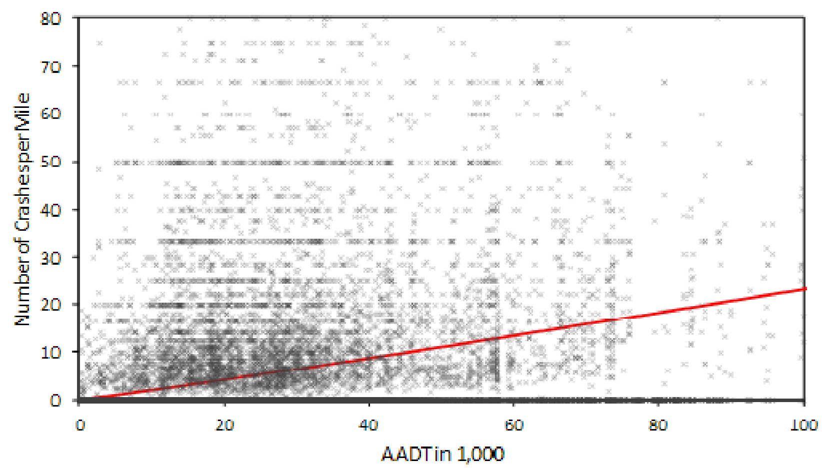
(a) Rural undivided segments



(b) Rural divided segments



(c) Urban undivided segments



(d) Urban divided segments

Figure C1. Observed Crash Frequency and Safety Performance Functions of Multilane Highways in Virginia. AADT = annual average daily traffic (vehicles per day).