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Virginia Transportation Research Council

research report

Development of Safety Performance Functions for Two-Lane Roads Maintained by the Virginia Department of Transportation

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16. Abstract:

In recent years, significant effort and money have been invested to enhance highway safety. As available funds decrease, the allocation of resources for safety improvement projects must yield the maximum possible return on investment. Identifying highway locations that have the highest potential for crash reduction with the implementation of effective safety countermeasures is therefore an important first step in achieving the maximum return on safety investment.

This study was undertaken to develop safety performance functions (SPFs) for use in Virginia in conjunction with SafetyAnalyst™, a computerized analytical tool that can be used for prioritizing safety projects. A *safety performance function* is a mathematical relationship (model) between frequency of crashes by severity and the most significant causal factors of crashes for a specific type of road. Although the *SafetyAnalyst User's Manual* recommends four SPFs for two-lane segments, these SPFs were developed using data from Ohio. Because the transferability of these SPFs to other states could not be guaranteed by the developers of the four recommended SPFs, it is necessary to calibrate or develop valid SPFs for each state using appropriate data from the state.

In this study, annual average daily traffic (AADT) was used as the most significant causal factor for crashes, emulating the SPFs currently suggested by Safety Analyst. SPFs for two-lane roads in Virginia were developed for total crashes and combined fatal plus injury crashes through generalized linear modeling using a negative binomial distribution for the crashes. Models were developed for urban and rural areas separately, and in order to account for the different topographies in Virginia, SPFs were also separately developed for three regions in Virginia. A total of 139,635 sites were identified for use in this study. Each site is a segment of a rural or urban two-lane road without an intersection for which AADT data were available for the years 2003 through 2007 inclusive and no change in facility type had occurred over that period. A comparative analysis based on the Freeman-Tukey R^2 coefficient was then conducted between the relevant Ohio SPFs suggested for use in the *SafetyAnalyst User's Manual* and those specifically developed in this study for Virginia to determine which set of models better fit the Virginia data. In general, the results indicated that the SPFs specifically developed for Virginia fit the Virginia data better.

The final step in this methodology was to illustrate the value of SPFs developed through an analysis of sample sites and the need of the sites for safety improvement based on SPFs as compared to crash rates. The results indicated that prioritization using the empirical Bayes method that incorporates the SPFs resulted in a higher potential for reduction in crashes than did prioritization using crash rates.

The effective use of SafetyAnalyst will facilitate the identification of sites with a high potential for safety improvement, which, in turn, with the implementation of appropriate safety improvements, will result in a considerable reduction in crashes and their severity.

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FINAL REPORT

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS FOR TWO-LANE ROADS MAINTAINED BY THE VIRGINIA DEPARTMENT OF TRANSPORTATION

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

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

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INTRODUCTION

Virginia has aggressive goals in place for the improvement of highway safety by 2010: reduce the number of fatalities by 100 and the number of injuries by 4,000 caused by motor vehicle crashes from the 2005 levels. These reductions comprise interim goals to achieving Virginia's broader vision to make Virginia's surface transportation system the safest in the nation by 2025 (Virginia's Surface Transportation Safety Executive Committee, 2006). Although these goals are being achieved, traffic engineers are still placing an increasing emphasis on using the empirical Bayes (EB) method, which uses safety performance functions (SPFs), to identify sites with the largest potential for safety improvement (PSI) to achieve the greatest possible safety benefit on highways. The PSI is measured as the difference between the long-term average of the collisions anticipated and the expected safety performance of a given site (Harwood et al., 2004).

A *safety performance function* is a mathematical relationship that models the frequency of crashes by severity and the causal factors for these crashes on specific types of roads. For example, crashes for a given time period can be estimated based on vehicle exposure. For a highway segment, exposure can be measured by the number of vehicles on the road segment and the distance for which they are exposed. An example of an SPF and how it is used in site prioritization is provided in Figure 1.

As shown in Figure 1, SPFs are used to determine the PSI for a given site, which is then used to prioritize sites by their safety needs. For each site with a given number of observed crashes, the EB-adjusted long-term estimated crashes is calculated based on a combination of the observed and predicted crashes. The difference between this value and the number of crashes predicted by the SPF is the PSI. Sites with a larger PSI receive a higher prioritization when all sites are ranked across the network to determine which sites should receive the greatest attention.

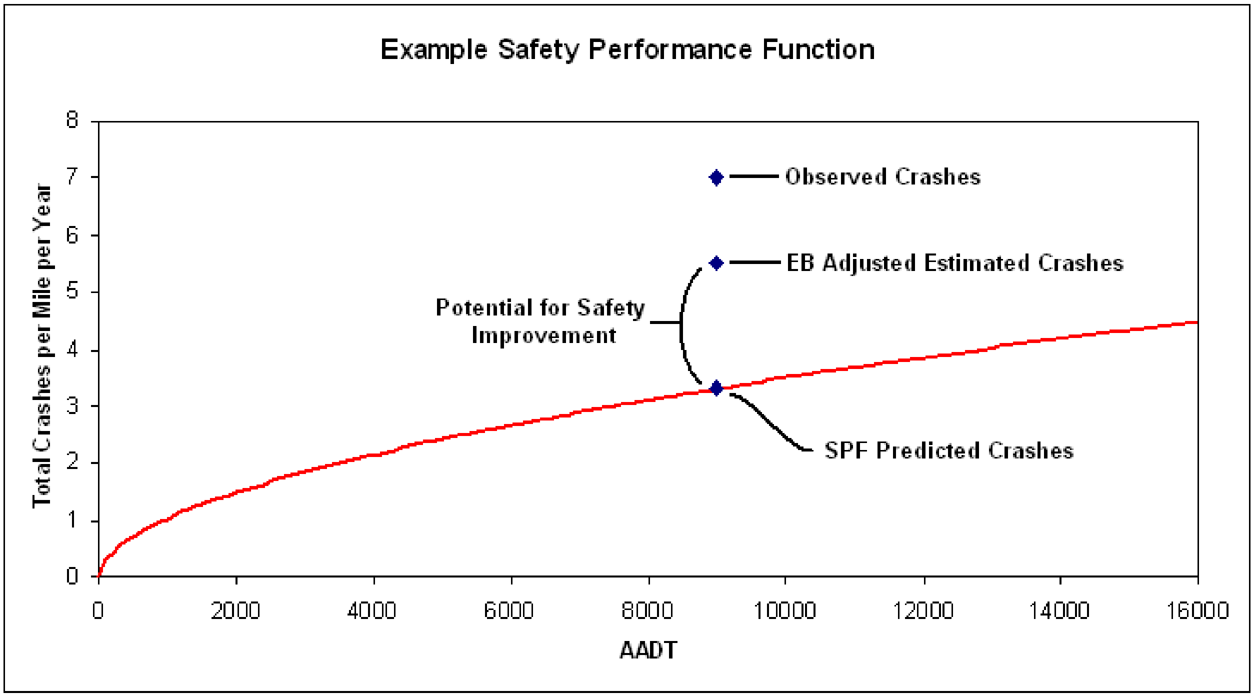

Figure 1. Example Safety Performance Function (SPF). EB = empirical Bayes; AADT = average annual daily traffic.

The use of SPFs facilitates the identification of locations that will have the greatest beneficial effects from the implementation of safety countermeasures. This is particularly useful because of the limited funding available for implementing safety improvement projects, as it ensures the greatest improvement for each dollar spent. Once high risk locations have been identified, countermeasures can be selected based on causal factors for the crashes prevalent at the specific site. Causal factors for two-lane and multi-lane highways in Virginia were previously identified through the development of crash estimation models (Garber et al., 2009; Garber and Kassebaum, 2008). Crash estimation models relate causal factors for a specific type of road characteristic and crash type to the estimated number of crashes.

The Federal Highway Administration (FHWA) recognized the need for SPFs as it developed SafetyAnalyst™ software as a cooperative effort of FHWA and participating state and local agencies (FHWA, undated). The software will be transitioned to become a licensed AASHTOWare product for Fiscal Year 2010. SafetyAnalyst provides a set of software tools for use by state and local highway agencies for highway safety management. These tools can be used to improve the programming of site-specific highway safety improvements following the process and procedures that will be in the forthcoming *Highway Safety Manual* (HSM). SafetyAnalyst incorporates the HSM safety management approaches into computerized analytical tools for guiding the decision-making process. Because it has a strong basis in cost-effectiveness analysis, SafetyAnalyst can play an important role in prioritizing improvements so that highway agencies get the greatest possible safety benefit from each dollar spent in the name of safety (American Association of State Highway and Transportation Officials, 2009).

The software for SafetyAnalyst uses SPFs for three of the four functional modules: (1) network screening for site identification, (2) economic analysis and countermeasure ranking, and

(3) effectiveness evaluation of implemented countermeasures. SPFs are used for a variety of types of sites, including two-lane roads, multi-lane roads, interstates, ramps, and intersections (Harwood et al., 2004). As a consequence, SPFs play an essential role in multiple facets of SafetyAnalyst and are vital to its effective application.

Based on their critical role in SafetyAnalyst, function in effective countermeasure implementation, and role in utilizing previous causal factor research, the development of SPFs for Virginia is an important step in improving Virginia's highway safety. SPFs have been developed across other states with varying degrees of success (Harwood et al., 2004). However, no effort has been made to test the transferability of these models to Virginia's unique characteristics.

PURPOSE AND SCOPE

The purpose of this study was to develop a set of SPFs for various conditions on two-lane highway segments that could be used to prioritize the need for safety improvement projects in Virginia. The set of SPFs to be developed was to include total crashes and combined fatal plus injury crashes covering different configurations (four-leg and three-leg intersections) and control systems (signalized and unsignalized intersections) across rural and urban locations.

The scope of the study was limited to two-lane road segments in Virginia maintained by the Virginia Department of Transportation (VDOT).

Although the study was not concerned with city roads that are not maintained by VDOT, the urban functional classification has many miles of subdivision streets of various designs in Virginia's counties. Intersections and intersection-related crashes are being investigated in a separate study currently in progress (Garber and Rivera, 2008).

The development of countermeasures and assessments of their effectiveness were outside the scope of this study.

METHODS

Eight tasks were conducted to achieve the study objectives:

1. literature review
2. site selection
3. collection of crash data
4. collection of operational data
5. evaluation of existing models

6. generalized linear modeling (GLM)
7. site prioritization
8. model tree pruning.

Literature Review

The relevant literature falls into two primary categories: SPFs and crash prediction models. Both are important in understanding and improving highway safety. Crash prediction models are expected to show higher goodness of fit values, such as R^2, because they relate multiple causal factors to the number of crashes. SPFs are useful even with lower goodness of fit measures because they are more concerned with site prioritization than prediction of the exact number of crashes.

Results of previous studies were used to examine modeling techniques and factors affecting crashes. Recent publications and studies regarding two-lane crashes were identified using the Transportation Research Information Service (TRIS), the VDOT Research Library, and libraries at the University of Virginia. The materials identified were critically reviewed and summarized to identify results relevant to this study.

Site Selection

The SPFs developed in this study were based on segments of rural and urban two-lane highways in Virginia for which annual average daily traffic (AADT) data were available for the years 2003 through 2007 inclusive and no change in facility type occurred during that period. The study made use of segments (study sites) of two-lane roads maintained by VDOT such that any change in a facility constituted a segment break. Such changes include speed limit alterations, shoulder width, facility type, AADT, and all intersections. Each of the resulting sites was reduced in length according to the number of intersections encountered, a number always between 0 and 2. The effective site length used to develop SPFs was the true length less 250 ft for each intersection encountered. Intersections were always at segment ends, so no site contained an internal intersection. Figure 2 shows VDOT's nine districts. The mileage and proportions for sites selected in each district are provided in Table 1.

Further categorization of the final sites selected, including the rural and urban breakdown and primary and secondary mix, is provided in Table 2. Roadways are categorized by VDOT according to their predominant role in the network (primary or secondary) and their physical location (urban or rural). Typically, the level of mobility, land access, and physical location determine the role of the roadway.

As evident in Table 2, the majority of the 139,635 sites are part of the secondary roadway network. This was as expected as the majority of two-lane mileage is secondary. There were 82,030 rural sites and 57,605 urban sites. As expected, the urban sites were primarily located in the Northern Virginia and Richmond districts. The mileage represented by the rural sites was comparatively larger (58.7%) than for the urban sites (41.3%) by virtue of longer contiguous facilities without changes in type or intersections.

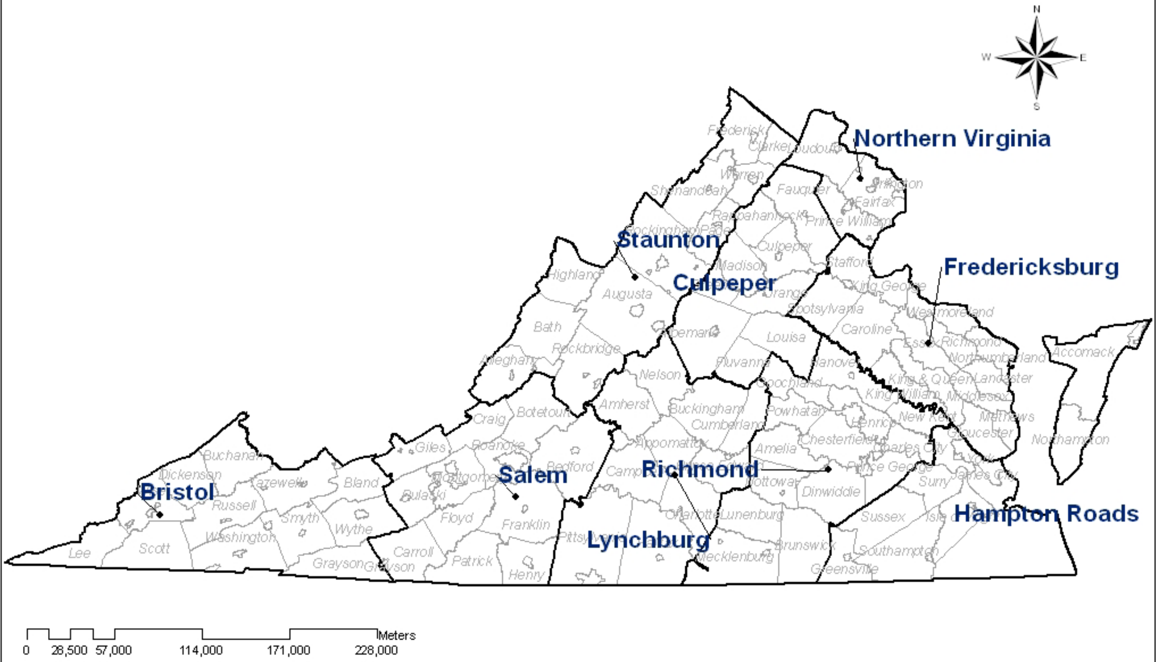

Figure 2. VDOT's Nine Districts

Table 1. Proportion of Selected Sites per District[a]

Jurisdiction (District No.)	Two-Lane Mileage of Sites (mi) (km)	Mileage[a] Proportion (%)
Bristol (1)	5,956 (9927)	14.3
Salem (2)	6,502 (10837)	15.6
Lynchburg (3)	5,972 (9953)	14.3
Richmond (4)	5,562 (9270)	13.3
Hampton Roads (5)	3,068 (5113)	7.3
Fredericksburg (6)	3,773 (6288)	9.0
Culpeper (7)	3,761 (6268)	9.0
Staunton (8)	5,052 (8420)	12.1
Northern Virginia (9)	2,151 (3585)	5.1
Total	41,797 (69660)	100

[a] Based on 2009 VDOT data.

Table 2. Distribution of Number of Study Sites by VDOT District

Jurisdiction (District No.)	Rural Primary	Rural Secondary	Urban Primary	Urban Secondary
Bristol (1)	2007	9671	210	943
Salem (2)	1455	12212	200	3834
Lynchburg (3)	1701	8337	52	1498
Richmond (4)	1496	8203	539	13983
Hampton Roads (5)	859	5968	221	2671
Fredericksburg (6)	1280	8255	99	4183
Culpeper (7)	1224	6390	24	783
Staunton (8)	2000	9111	133	1465
Northern Virginia (9)	319	1542	265	26052
Total	12341	69689	1743	55862

Collection of Crash Data

The data were obtained primarily from VDOT's Highway Traffic Records Information System (HTRIS). HTRIS is a comprehensive Oracle database system that interrelates and consolidates Virginia's highway and traffic information used for internal management and reporting. VDOT maintains detailed records on current and historical roadway, crash, and traffic information in HTRIS. HTRIS contains multiple subsystems, three of which were joined to extract data for this study: roadway inventory (RDI) for segment lengths, accident (ACC) for crash counts, and the traffic management system (TMS) that uploads data from HTRIS for AADT.

The ACC crash database is compiled from crash report forms (DMV Form No. FR300) filled out by the police officer responding to a crash. These forms contain a wide variety of information about the crash including location, driver's actions, driver characteristics, collision type, environmental conditions, severity, and other factors pertinent to the crash. For each site, total and fatal plus injury yearly crash counts were extracted from the ACC subsystem of HTRIS. Crashes reported within 250 ft of an intersection were excluded from this study because of the differing characteristics of intersection crashes and road segment crashes. SPFs for these intersection locations are being developed under a concurrent study (Garber and Rivera, 2008).

Collection of Operational Data

Five years (2003-2007) of RDI and TMS data were collected and retrieved from HTRIS. The RDI contains about 62,000 centerline miles of roadway information including characteristics, function, physical condition and location, administrative classification, and ownership. The RDI identifies the roadway segments with a unique ID, and each data segment presents elements that describe a specific portion of the roadway feature and characteristics. Through the use of the 5 years of RDI records, the selected study sites consisted of two-lane facilities that sustained the same geometric and topographical conditions during the study window.

Evaluation of Existing SPFs

Once the necessary data had been collected and prepared for each of the 139,635 sites, the next step was to test the transferability of interim SPFs created during the development of SafetyAnalyst to Virginia's two-lane roads. The basic form of these SPFs was as follows:

$$\text{Crashes} = e^{a} \times \text{AADT}^{b} \times \text{SL} \qquad \text{[Eq. 1]}$$

where

Crashes = predicted crashes per year
AADT = average annual daily traffic (vehicles/day)
SL = segment length (miles)
a and b = regression parameters.

Each of the four SafetyAnalyst interim SPFs for rural roads, i.e., those of Minnesota, North Carolina, Washington, and Ohio, and three SafetyAnalyst interim models for urban roads, i.e., those of Minnesota, Washington, and Ohio, were compared to the data collected in Virginia using graphical and statistical methods. The numbers of years for which data were used to develop these interim SPFs were five for Minnesota, three for Ohio, and four for Washington. This information was not given for North Carolina (ITT Corporation, 2008). The Virginia crash data were aggregated over the 5-year time frame for these comparisons, as each site then represented a single data point. The rural and urban SPFs for total crashes developed for interim use in SafetyAnalyst are illustrated in Figures 3 and 4.

In addition to the graphical comparison of data from Virginia's two-lane sites and the SPFs developed for SafetyAnalyst, the coefficient of determination, R^2, and the Freeman-Tukey R^2 (R_{FT}^2) coefficient were calculated to examine how well the SafetyAnalyst models fit the Virginia data. Equations 2 through 4 were used to calculate R^2.

$$R^2 = 1 - SS_{er}\ SS_{tot} \quad \text{[Eq. 2]}$$

$$SS_{err} = \sum_i (y_i - y_m)^2 \quad \text{[Eq. 3]}$$

$$SS_{tot} = \sum_i (y_i - m_i)^2 \quad \text{[Eq. 4]}$$

where

R^2 = coefficient of determination
y_i = observed data at site i
y_m = mean of observed data across all sites
m_i = modeled (predicted) value at site i.

The Freeman-Tukey R_{FT}^2 coefficient was used in the development of SPFs for SafetyAnalyst to represent the goodness of fit of the negative binomial regression models. Equations 5 through 7 show how the data were transformed to calculate the R_{FT}^2 (Fridstrøm et al., 1994).

$$f_i = (y_i)^{0.5} + (y_i + 1)^{0.5} \quad \text{[Eq. 5]}$$

$$\hat{e}_i = f_i - (4 \times \hat{y}_i + 1)^{0.5} \quad \text{[Eq. 6]}$$

$$R_{FT}^2 = 1 - \sum_i \hat{e}_i^2 / \sum_i (f_i - f_m)^2 \quad \text{[Eq. 7]}$$

where

f_i = Freeman-Tukey transformation statistic
y_i = observed data at site i
$\hat{e}_i$ = residual at site i
$\hat{y}_i$ = modeled (predicted) value at site i
f_m = mean of the transformation statistic across all sites.

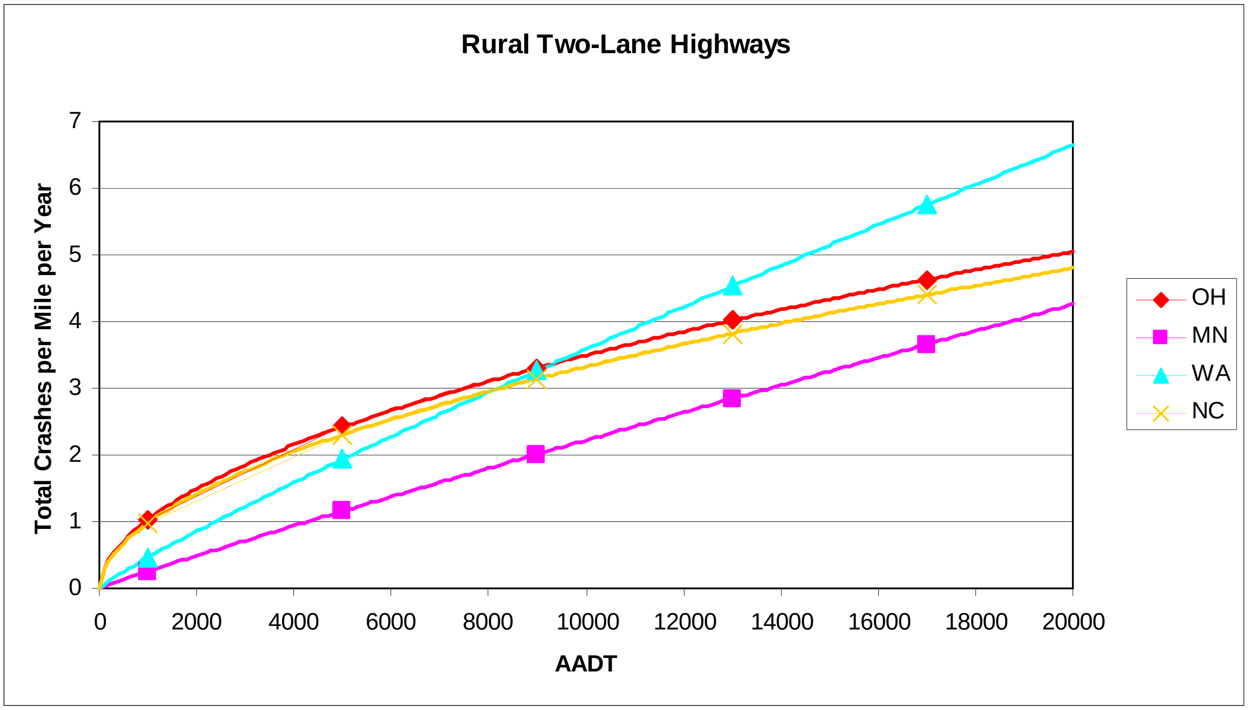

Figure 3. Safety Analyst SPFs for Rural Two-Lane Highway Segments.
OH: Crashes = $e^{-3.63}$ × $AADT^{0.53}$ /mi/yr **MN: Crashes = $e^{-7.86}$ × $AADT^{0.94}$/mi/yr**
WA: Crashes = $e^{-6.92}$ × $AADT^{0.89}$/mi/yr **NC: Crashes = $e^{-3.68}$ × $AADT^{0.53}$/mi/yr**

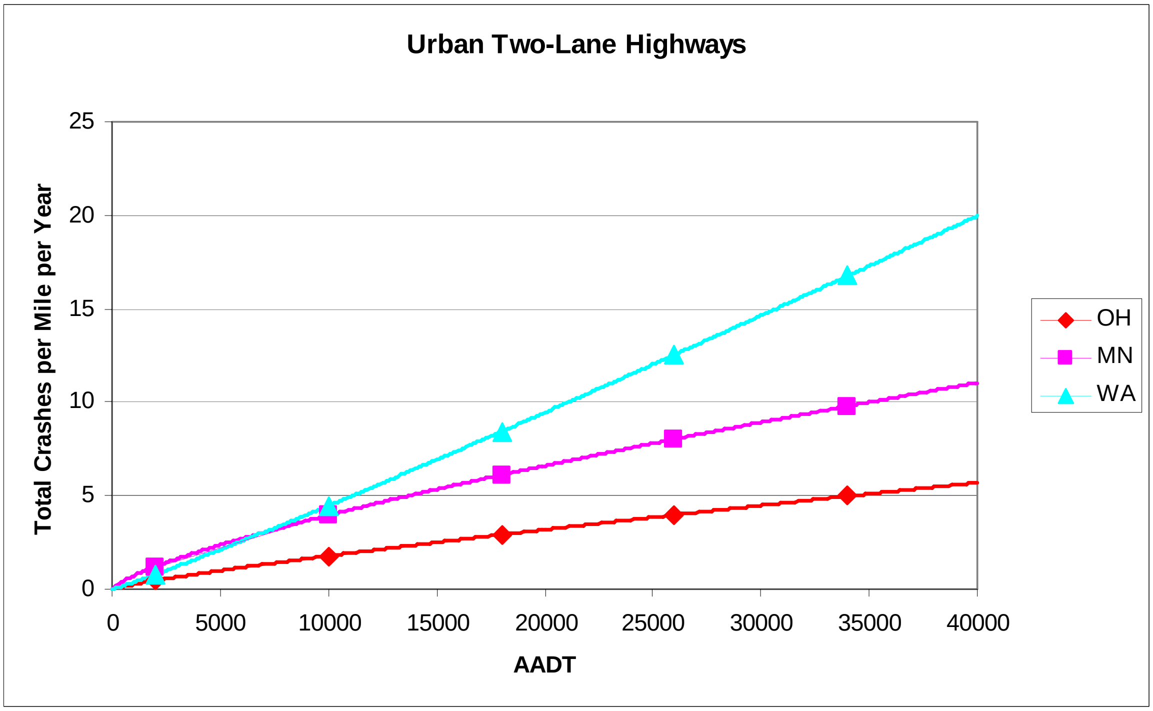

Figure 4. SafetyAnalyst SPFs for Urban Two-Lane Highway Segments.
OH: Crashes = $e^{-7.16}$ × $AADT^{0.84}$/mi/yr **MN: Crashes = $e^{-5.44}$ × $AADT^{0.74}$/mi/yr**
WA: Crashes = $e^{-8.45}$ × $AADT^{1.08}$/mi/yr

In using graphical methods and the R^2 and R_{FT}^2 calculations to test the transferability of the existing SPFs developed for SafetyAnalyst to the selected sites in Virginia, the expectation was that the model fit would not be optimal. This was expected as these models were developed under conditions different from those of Virginia's two-lane roads. Each of the models from SafetyAnalyst is valid only for application to the state and time period for which each was developed (Harwood et al., 2004). SafetyAnalyst does provide a calibration procedure that allows for SPFs to be applied to other states and time periods. The calibration procedure introduces a yearly factor (c_y) into the original SPF model form (Eq. 1); the calibrated model form is shown in Equation 8 (ITT Corporation, 2008).

$$\text{Crashes} = c_y \times e^a \times \text{AADT}^b \times \text{SL} \qquad \text{[Eq. 8]}$$

where

Crashes = predicted crashes per mile per year
c_y = calibration factor for year y
AADT = average annual daily traffic (vehicles/day)
SL = segment length (miles)
a and b = regression parameters from SafetyAnalyst models.

It should be noted that this yearly calibration factor is limited because it is an average statewide or areawide shifting factor of the curve up or down that is not adjusting the shape based on AADT.

The yearly calibration factor is calculated using Equation 9 (ITT Corporation, 2008).

$$c_y = K_y/\kappa_y \qquad \text{[Eq. 9]}$$

where

c_y = calibration factor for year y
K_y = total number of observed crashes across all sites for year y
κ_y = total number of predicted crashes over all sites for year y.

Generalized Linear Modeling

Although the previously described calibration procedure for SafetyAnalyst's SPFs does seek to improve the model fit, it can be accurate only to some extent, as the model coefficients are not modified. To provide more accurate SPFs that can be applied in Virginia, new models should be created that are based directly on the Virginia data. To create these SPFs, GLM was used to provide the relationship between the AADT and the number of crashes per mile per year for each site. For statistical modeling, the software package SAS 9.1.3 was used (SAS Institute Inc., 2009). The GENMOD procedure in SAS was used with a logarithmic link function and a negative binomial distribution. A negative binomial distribution was selected in accordance with the models developed for SafetyAnalyst (Harwood et al., 2004). The equation resulting from the GENMOD procedure is given in Equation 10.

$$Y = \exp(a + b \times X) \qquad \text{[Eq. 10]}$$

where

Y = dependent variable
X = independent variable
a and b= regression parameters.

For the purposes of developing SPFs, the dependent variable is the expected crashes per mile per year and the independent variable is the AADT. To manipulate the equation into the desired SPF form, shown in Equation 10, the independent variable must be entered as the natural log of the AADT. The crashes for each site are divided by the site length to yield crashes per mile. Seventy percent of the data set (training data) was used to develop the SPFs, and the remaining 30% was used for validation. The two primary SPFs developed for use in SafetyAnalyst were those for all rural two-lane roads and all urban two-lane roads. In this study, SPFs were also developed based on a further breakdown of the characteristics of Virginia's two-lane roads. This breakdown was based on functional and administrative classifications and geographic location. The geographic regions for Virginia are based on VDOT's five operational regions. The regions, created in 2006, are grouped based on commuting patterns, traffic routes, crash statistics, driver behavior, and topography (Armstrong, 2006). The five operational regions are illustrated in Figure 5.

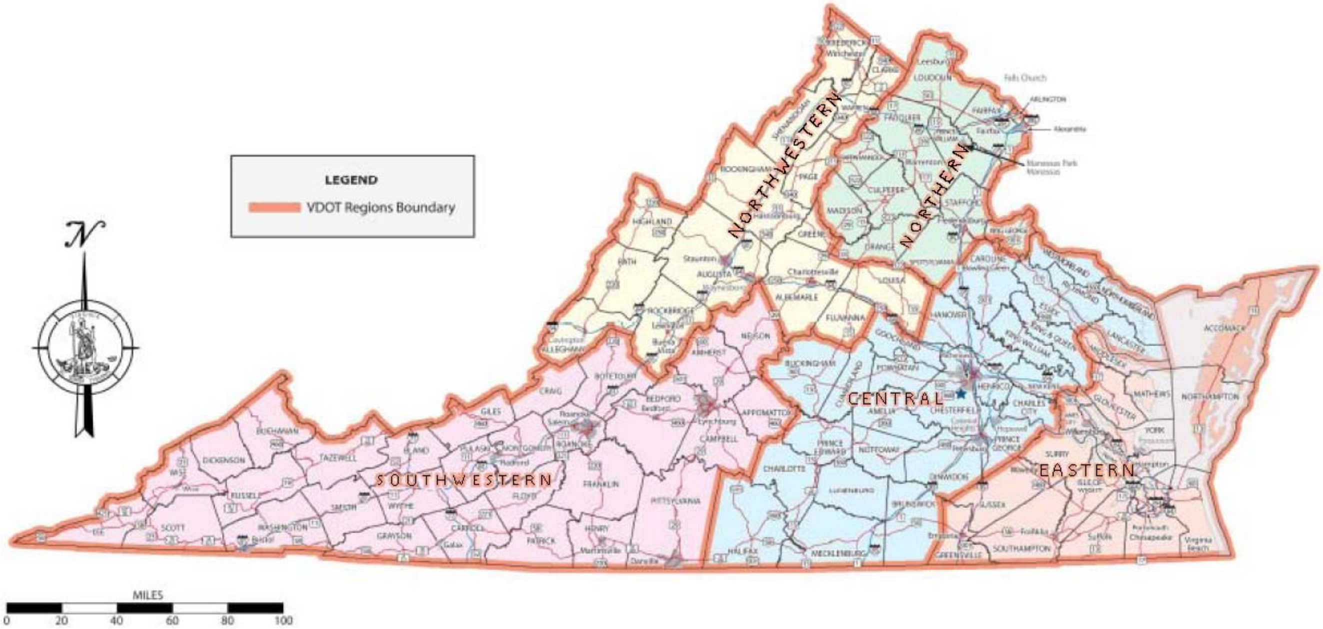

Figure 5. VDOT's Five Operational Regions

The three geographic regions grouped for this study were the Northern Operation Region (Northern), the Northwest and Southwest Operation Regions (Western), and the Central and Eastern Operation Regions (Eastern). These three regions were determined in conjunction with staff of VDOT's Traffic Engineering Division based on physical road characteristics, topography, driver characteristics, and operational characteristics (S. Read, personal communication, 2009). The breakdown by region will at least partially account for the differing characteristics across Virginia. For example, rural two-lane roads in the Northern Virginia District are very different in volume, geometry, and driver behavior from rural two-lane roads in Southwestern Virginia. It could be argued that the inclusion of the Culpeper District in the Northern Region for this study was questionable because of its more rural characteristics. This, however, does not have much impact on the SPFs developed for this region as they were developed for urban and rural roads separately.

With these three geographic regions selected for separate analysis and the statewide SPFs, there were 72 possible model cases for potential development. The breakdown for the statewide SPFs is shown in Figure 6.

To examine the fit of each model, the R^2 and R_{FT}^2 values were calculated using the 70% training data set. In addition, the transferability of the developed models was evaluated using the 30% of the data saved for model validation. The mean square prediction error (MSPE) was used for this comparison.

The 36 potential SPF cases (18 statewide and 18 for each of the three geographic regions) shown in Figure 6 were developed for both total crashes and fatal plus injury crashes alone for a total of 72 possible models. The selection algorithm ensured that the total mileage of the 30% and 70% samples was proportionate to the number of sites.

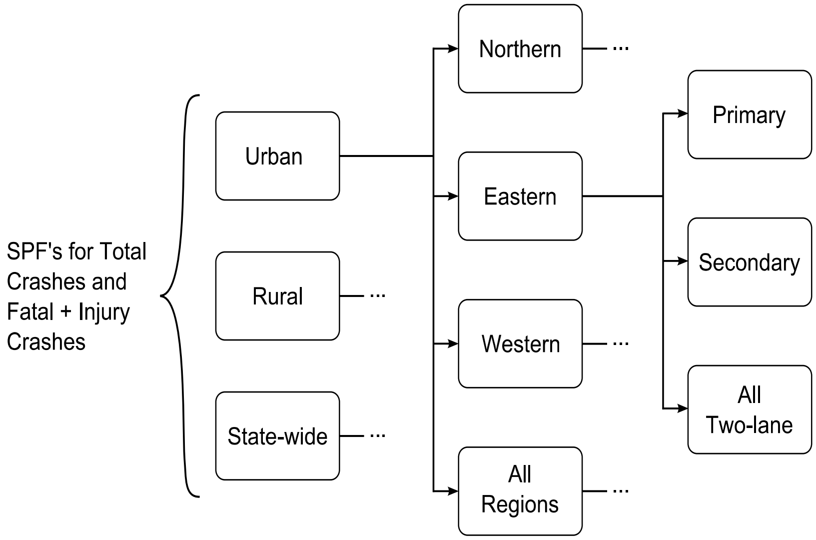

Figure 6. Virginia Statewide SPFs Developed. Ellipses indicate the same pattern repeating but omitted for clarity.

Site Prioritization

It is highly likely that VDOT will soon be using the EB method for prioritizing sites for safety improvement, which will require SPFs that reflect the impact of AADT on crashes in Virginia. To show the benefits of using SPFs for the prioritization of safety improvement projects, the use of SPFs for two randomly selected districts, Culpeper (No. 7) and Staunton (No. 8), was compared with that of corresponding crash rates for the ranking of sites. The crash rate was calculated for each site, given in crashes per million vehicle miles traveled (VMT). These crash rates, based on the aggregated 2003 (year 1) to 2007 crash and volume data, were then used to rank the sites in terms of PSI.

Site ranking with the use of SPFs used the EB method and was performed using the method outlined in the *SafetyAnalyst User's Manual* (ITT Corporation, 2008). The first step was to calculate the predicted crashes for each year based on the applicable SPF, urban total crashes, for example. Equations 8 and 9 were used to perform this step. Next, the yearly correction factor, C_y, was calculated for each year using Equation 11. The next step was to calculate the weighting factor, w, using Equation 12 (ITT Corporation, 2008). The dispersion parameter shown in Equation 12 is given by SAS for each model developed and is estimated by maximum likelihood.

$$C_y = \kappa_y / \kappa_1 \qquad \text{[Eq. 11]}$$

where

C_y = yearly correction factor for year y
κ_y = total number of predicted crashes for year y
κ_1 = total number of predicted crashes for year 1.

$$w = \frac{1}{1 + d \times \sum_{y=1}^{Y} \kappa_y} \qquad \text{[Eq. 12]}$$

where

w = weighting factor
d = dispersion parameter for the SPF used
κ_y = total number of predicted crashes for year y.

With the yearly correction factors and weighting factors calculated, the EB-adjusted expected number of crashes was then determined for each site during year 1 on a per-mile basis using Equation 13 (ITT Corporation, 2008).

$$X_1 = w \times \kappa_1 + \frac{1-w}{W} \times \frac{\sum_{y=1}^{Y} K_y}{\sum_{y=1}^{Y} C_y} \qquad \text{[Eq. 13]}$$

where

X_1 = EB adjusted number of crashes per mile for year 1
w = weighting factor
W = site length (miles)
κ_1 = predicted crashes for year 1
K_y = total number of observed crashes for year y
C_y = yearly correction factor for year y.

Finally, the EB-adjusted expected crashes in year 1 were multiplied by the yearly correction factor, C_y, to find the EB-adjusted expected crashes for each year across each site. The excess number of crashes at each site was then determined by subtracting the average crashes over the study period predicted by the SPF (calculated with Eq. 8) from the average long-term EB-adjusted expected crashes over the same period (calculated with Eqs. 11 through 13) (ITT Corporation, 2008). To present the results in a more useful format, a rolling window of length 0.25 mi was applied to continuous segments of roadway with an incremental step of 0.0625 mi (330 ft or ¼ the window length). In this way, a weighted average of the EB-expected excess crashes was computed for these windowed sites. In cases where the data could not provide segments at least 0.25 mi long, the total available length of the segment was used. These windowed sites are presented in the prioritization results, ordered by the long-term EB-expected crash reduction for the site, irrespective of the length of the window, with sites showing a higher excess number of crashes receiving a higher priority. SafetyAnalyst executes a similar procedure for fatal and injury crashes and uses relative severity weights to calculate an equivalent property damage only total for each location that is then examined for excess crashes (ITT Corporation, 2008).

Model Tree Pruning

For simplicity of implementation, an algorithm was developed to prune the full tree of 72 models where the specificity of a model devoted to a particular region or primary/secondary designation was found to be redundant with a more general model. This evaluation was conducted by comparing MSPEs for the specific models with those for the corresponding general model. A specific model was discarded when its MSPE was at least 98.5% that of the general model. The MSPEs for this analysis were computed using the 30% evaluation data to avoid susceptibility to an over-trained model, which might have occurred if the 70% set of training data had been used. First, regional specificity was considered for urban, rural, and urban + rural combined models for both total and fatal and injury crashes only and for combined primary and secondary sites. Evaluation data only for the region in question were used to calculate the MSPEs for the specific regional model and the more general statewide model. Second, models specific only to primary or secondary highways were evaluated for redundancy against the regionally pruned general model tree.

RESULTS

Literature Review

Safety Performance Functions

SafetyAnalyst is strongly based on the cost-effectiveness of a given safety improvement; because of this, the comparison of sites and their PSI is very important. As stated previously, in the development of the two-lane SPFs for SafetyAnalyst, four models, from Ohio, Washington, Minnesota, and North Carolina, were created and analyzed (Harwood et al., 2004). All the models developed for road segments in SafetyAnalyst follow the same base form, shown again in Equation 14

$$\text{Crashes} = e^{a} \times \text{AADT}^{b} \times \text{SL} \qquad \text{[Eq. 14]}$$

where

Crashes = predicted crashes per year
AADT = average annual daily traffic (vehicles/day)
SL = segment length (miles)
a and b = regression parameters.

In addition to this base model form, the SafetyAnalyst model form includes a yearly calibration factor and a proportion factor if crashes of a specific type are being investigated. Although highway characteristics such as lane width, shoulder width, and driveways are not directly incorporated into the model, they can be taken into account by developing different regression parameters based on the geometric conditions. Although this has not been included in the interim version of SafetyAnalyst, it may be introduced at a later point or on a state level (Harwood et al., 2004). The model parameters for rural and urban two-lane highway segments are provided in Tables 3 and 4, respectively.

Table 3. SafetyAnalyst Rural Two-Lane Highway Segments SPFs

State	Regression Coefficients		Overdispersion Parameter	R_{FT}^2 (%)	Total Length of Sites (mi)	Maximum AADT (veh/day)
	Logntercept (a)	LogAADT (b)				
SPFs for Total Accidents						
MN	-7.86	0.94	0.48	56.1	26,920	31,461
NC	-3.68	0.53	0.56	71.8	25,102	28,808
OH[a]	-3.63	0.53	0.50	72.5	12,412	30,025
WA	-6.92	0.89	0.27	60.7	5,255	23,918
SPFs for Fatal and Injury Accidents						
MN	-8.01	0.83	0.43	46.1	26,920	31,461
NC	-4.71	0.55	0.67	65.8	25,102	28,808
OH[a]	-4.86	0.53	0.67	59.9	12,412	30,025
WA	-7.50	0.88	0.29	54.3	5,255	23,918

Source: Harwood et al. (2004).
[a] SafetyAnalyst-recommended SPFs.

Table 4. SafetyAnalyst Urban Two-Lane Arterial Segments SPFs

State	Regression Coefficients Logntercept (a)	Regression Coefficients LogAADT (b)	Overdispersion Parameter	R_{FT}^2 (%)	Total Length of Sites (mi)	Maximum AADT (veh/day)
SPFs for Total Accidents						
MN	-5.44	0.74	1.85	6.2	12,032	30,000
OH[a]	-7.16	0.84	4.40	13.6	1,504	29,850
WA	-8.45	1.08	0.71	19.2	252	29,932
SPFs for Fatal and Injury Accidents						
MN	-7.78	0.86	1.58	11.5	12,032	30,000
OH[a]	-8.84	0.89	4.54	14.0	1,504	29,850
WA	-9.64	1.12	0.64	22.2	252	29,932

Source: Harwood et al. (2004).

[a] SafetyAnalyst-recommended SPFs.

As seen in Table 3 for rural two-lane highway segments, the Ohio model was selected for use in interim development because of its high R_{FT}^2 and the fact that its form, nearly a square root function, fits the expectation of the appropriate shape of crash prediction models (Harwood et al., 2004). All four states have reasonably good models for total crashes, as the R_{FT}^2 for all rural models exceed 0.56. The North Carolina and Ohio models have a logAADT coefficient of 0.53, which is very close to a square root function. The Washington and Minnesota SPFs are nearly linear, with a logAADT coefficient close to 1.0 (Harwood et al., 2004). With these two distinct model shapes, it was important to investigate which shape, if either, best fits Virginia data.

The SPFs in Table 4, showing the regression parameters for urban two-lane arterial segments, display very low R_{FT}^2 values. None of these urban models fits as well as their rural counterparts. The developers of SafetyAnalyst think that other variables, such as number of driveways, may need to be included in addition to AADT to explain more of the observed crashes (Harwood et al., 2004). Only the Ohio and Minnesota models have logAADT coefficients less than 1.0; of these, Ohio has the higher R_{FT}^2, so it was selected for use in the interim tools (Harwood et al., 2004). It is clear that there is significant room for improvement in these models as they are modified to fit Virginia's characteristics.

A study comparing the SPFs developed for SafetyAnalyst with one of similar form using New Zealand data was conducted . The New Zealand model predicted fewer crashes and took a shape similar to that of the SafetyAnalyst Minnesota model. This lower prediction likely stemmed from much lower crash reporting rates in New Zealand, which can be as much as one-half those in the United States (Turner et al., 2007).

Another study using international data and focusing primarily on the effects of AADT on crashes was performed in Ontario, Canada (Persaud, 1993). The study developed SPFs for rural roads and refined the model for a given section using an EB method. The model form shown in Equation 15 is the same as that used in SafetyAnalyst:

$$E(m) = Ln(AADT)^b \quad \text{[Eq. 15]}$$

where

E(m) = expected long-term annual crash potential of a section
AADT is in thousands of vehicles.

Geometric parameters were taken into consideration in the development of the regression parameter b. Distinct parameter values were calculated based on pavement width greater or less than 6.1 m (20 ft), shoulder width greater or less than 1.8 m (5.9 ft), and high- or low-quality surface. These models were generated with the intent of identifying locations with higher than expected crashes and evaluating safety treatments in these locations (Persaud, 1993).

Another international study to develop SPFs for two-lane roads was performed in the United Kingdom (Mountain et al., 1996). The data were obtained from injury and fatal crashes in seven counties in the United Kingdom and included only A and B classified highways. Roads classified as A and B are nonmotorways (freeways), with the A roads being the main trunk roads serving as connectors between major cities (analogous to Virginia's primary system) and the B roads having lower traffic densities than the A roads (analogous to Virginia's secondary system). The general form of the model is:

$$\mu = \alpha_1 t^{\beta 1} l^{\beta 2} exp(bn/l) \qquad \text{[Eq. 16]}$$

where

μ = predicted annual crashes
t = total two-way annual link traffic flow (million vehicles/year)
l = segment length (kilometers)
n = number of minor junctions within the link
α_1, β_1, β_2, and b, = model coefficients.

The model coefficients, α_1, β_1, β_2, and b, were calculated for six conditions based on the speed limit, number of lanes, and functional classification of the segment. Roads with a speed limit less than or equal to 40 mph were designated urban; roads with a speed limit greater than 40 mph were rural. The minor junctions played a significant role in many of the crashes, with one third of the urban crashes and one fifth of the rural crashes occurring at these locations (Mountain et al., 1996). Based on these observations, modeling the number of minor junctions in a given segment is important; however, for the purpose of the current study it is not necessary because all intersection crashes, both major and minor, were excluded and will be covered by a separate set of SPFs currently under development (Garber and Rivera, 2008).

Crash Prediction Models

In addition to the relatively simple SPFs previously discussed, there are many crash prediction models that include multiple independent variables in a variety of model forms. The independent variables taken into account vary from geometric parameters to geographical and traffic conditions. These models are used to predict the expected crashes for a given segment and to examine the impact of each contributing variable. The review of the literature pertaining to crash prediction models was used as a guide for the examination of the model form and variables that may have an effect on the likelihood of crashes.

One such study performed at the Connecticut Transportation Institute investigated the relationship between traffic volume and specific crash types on rural two-lane segments using data from Michigan, California, Washington, and Illinois (Milton and Mannering, 1996). The base form of the crash prediction model was:

$$\ln(\mu) = \text{intercept} + \beta_Y(D_Y) + \beta_V \ln(V) + \beta_L \ln(L) + \beta_W W + \beta_S S \qquad \text{[Eq. 17]}$$

where

μ = number of crashes/year on a segment of length L (m)
D_Y = dummy variable to account year effects on the intercept
V = AADT
L = segment length (m)
W = pavement width (cm)
S = speed limit (km/h)
β_i = regression coefficients.

The regression coefficients were calculated for different models based on crash type, single vehicle, multi-vehicle same direction, multi-vehicle opposite direction, and multi-vehicle intersecting direction. The findings indicated that the relationship between crashes and traffic volume was nonlinear for each of the four crash types examined (Qin et al., 2005).

In an effort to determine the safety impact of converting two-lane roads to four-lane roads, Council and Stewart (1999) developed crash prediction models for two-lane and four-lane rural roads and for divided and undivided median types. Model coefficients were calculated for each state with data from North Carolina, Washington, Minnesota, and California. Number and type of intersections were not included in these models because of a lack of data for this variable in the Highway Safety Information System database and the assumption that the conversion from two-lane to four-lane would not dramatically affect intersection crashes; thus, intersection crashes were not taken into consideration, as was the case with the SPFs developed for SafetyAnalyst. Over-dispersed Poisson models were fitted to the data, and the base model form was as follows (Council and Stewart, 1999):

$$A = (\text{segment length})(e^{b0})(ADT^{b1})(e^{b2(\text{shoulder width})})\ (e^{b3(\text{surface width})}) \qquad \text{[Eq. 18]}$$

where

A = predicted accidents per year
b_i = regression coefficients.

Research performed in Denmark investigating crash prediction models for urban roads also used a Poisson distribution and multiple independent variables (Greibe, 2002). The model predicted accidents per kilometer per year and had the following structure:

$$E(\mu) = aN^{p}\beta_{1,i}\beta_{2,i}\beta_{3,i}\beta_{4,i}\beta_{5,i}\beta_{6,i}. \qquad \text{[Eq. 19]}$$

where

β_1 through β_6 = parameters based on speed limit, road width, number of exits per kilometer, number of minor side roads per kilometer, parking, and land use
N = AADT for the segment.
a, p, β_{ni} = estimated parameters.

Each of the β parameters is applicable for a range of values for a given characteristic. For example, if the speed limit is 50 km/h, then β_1 is 2.25; if the speed limit is 60 km/h, then β_1 is 2.85.

Results from this model indicated that 72% of the systematic variation could be explained by the variables in the model, with AADT being the most powerful, accounting for more than 30% of the variation (Greibe, 2002).

Another study performed in Turkey, based on an accident prediction model developed by Zegeer et al. (1987a), showed the significance of AADT in crash prediction. The model was as follows:

$$A = 0.0019(\mathrm{ADT})^{0.882}(0.879)^{w}(0.919)^{\mathrm{PA}}(0.932)^{\mathrm{UP}}(1.236)^{H} \times (0.882)^{T1}(1.322)^{T2} \qquad \text{[Eq. 20]}$$

where

A = number of crashes per mile per year
ADT = two-directional average daily traffic
w = lane width (feet)
PA = width of paved shoulder (feet)
UP = width of unpaved (gravel, turf, earth) shoulder (feet)
H = median roadside hazard rating for the highway segment, measured subjectively on a scale from 1 (least hazardous) to 7 (most hazardous)
$T1$ = 1 for flat terrain, 0 otherwise
$T2$ = 1 for mountainous terrain, 0 otherwise.

Based on a sensitivity analysis of the model using the fractional factorial method, AADT was found to be of primary importance and the other parameters and parameter interactions were found to be of secondary importance (Zegeer et al., 1987b). In addition to a measure of exposure, AADT plays a role in determining road geometry and hence is directly related to the number of crashes (Akgüngör and Yildiz, 2006).

Because of the over-dispersion of traffic data when a Poisson model is used, the variances of the model parameters tend to be underestimated. Because of this, the model may incorrectly estimate the likelihood of crash occurrence. In response to this issue, many studies chose to use a negative binomial distribution to model crashes. Milton and Mannering (1996) developed one such prediction model for the state of Washington. Using a negative binomial distribution, they included many independent variables, such as section length, vertical grade, AADT, peak hour percentage, truck percentage, speed limit, number of lanes, shoulder width, horizontal curves, and tangent curve length. They also developed different model coefficients for different road classifications and for geographical location, split between Eastern and Western Washington. This geographical split was significant in improving the accuracy of the crash prediction model and may be relevant in Virginia as there are distinctly different topographic conditions throughout Virginia.

Sawalha and Sayed (2001) used a negative binomial distribution because of over-dispersion of the data in developing a crash prediction model for urban roadways in the Greater Vancouver Regional District, British Columbia, Canada. Their final model was given as:

$$A_3 = 0.0228\ L^{0.7361}\ V^{0.6459} \exp(0.09097\ USD + 0.08274\ CROD + 0.08515\ NL + 0.1553\ I_{UND} + 0.01683\ DD\ I_{BUS}) \quad \text{[Eq. 21]}$$

where

A_3 = predicted accidents occurring over a 3-year period for a given road segment
L = segment length (kilometers)
V = annual average daily traffic (AADT)
USD = unsignalized intersection density per kilometer
$CROD$ = crosswalk density per kilometer
NL = number of lanes
DD = driveway density per kilometer
I_{UND} = indicator variable for undivided median treatment (1 if undivided, 0 otherwise)
I_{BUS} = indicator variable for business land use (1 if business, 0 otherwise).

Although all of these variables were found to affect crash occurrence, length and volume had the greatest impact (Sawalha and Sayed, 2001).

Bowman et al. (1995) also found that a negative binomial distribution was best in their development of crash prediction models for urban and suburban locations based on median conditions. Data sets from Atlanta, Phoenix, and Los Angeles were used for model development. Variables included AADT, accident report threshold, number of driveways, number of crossovers, speed limit, land use, median width, and number of crossroads. Some contradictory results were found, such as an increase in speed bringing a reduction in crashes according to their model; however, this was likely due to a reduction of development density and vehicle interactions at higher speeds (Bowman et al., 1995). This unexpected correlation between speed and predicted crashes provides a significant argument against using speed as a variable in SPFs.

Bonneson and McCoy (1997) engaged in similar research to develop an urban accident prediction model based on median treatment. They found that regression methods based on maximum-likelihood techniques and a negative binomial distribution of the residuals were necessary to calibrate crash prediction models accurately. They also stated that the relationship between crashes and exposure (ADT) is nonlinear; therefore, the use of crash rates is not an accurate predictor of crash frequency or highway safety. The general base form of their accident prediction model for urban locations was:

$$A = ADT^{(B0 + B1\ IU\ Ir/i)}\ Len^{B2}\ e^{(\text{linear terms})}. \qquad \text{[Eq. 22]}$$

where

A = accident per segment per year
ADT = average daily traffic
Len = length (m)
IU = indicator variable for undivided treatment (1.0 if undivided, 0.0 otherwise)
I_R = indicator variable for raise-curb median (1.0 if raised or 0.0 otherwise)
$I_{r/i}$ = indicator variable for residential or industrial land use (1.0 if residential or industrial, 0.0 otherwise)
Bi = regression coefficients.

The linear terms include factors such as median treatment, land use, driveway density, street density, and parking. Land use and AADT were found to have the greatest impact on the likelihood of crashes for a given location (Bonneson and McCoy, 1997).

In investigating the Poisson and negative binomial models to develop accident models for two-lane rural roads, Vogt and Bared (1998) concluded that further refinement was necessary. They used an extended negative binomial model for their study. In developing that model, segments were divided into subsections to account for geometric and traffic changes within a segment. This allowed for the model to address local conditions more precisely than an ordinary negative binomial model for two-lane segments that do not consider these variations within a segment. Variables analyzed included accident counts, traffic exposure, lane and shoulder width, roadside hazard rating, driveway density, channelization, horizontal and vertical alignments, speed limits, and commercial traffic percentage (Vogt and Bared, 1998). This crash prediction model was used in a later report on the prediction of the expected safety performance of rural two-lane highways. (Harwood et al., 2000) This report used Vogt and Bared’s base model along with a variety of crash modification factors. These factors are somewhat subjective as they are primarily based on expert judgment (Harwood et al., 2000). It should also be noted that models of this type are for project-level analysis where time and resources allow for data collection.

Virginia-Specific Research

The most significant previous research relating to SPFs conducted specifically for Virginia was done by Garber and Kassebaum (2008) in their evaluation of crash causal factors on two-lane highways in Virginia. Causal factor identification and corresponding countermeasure effectiveness were used after SPFs had been used to identify locations with higher-than-expected crashes. In the crash modeling presented by Garber and Kassebaum (2008), GLM and a logarithmic function were used to relate independent variables to the number of crashes. With these tools, countermeasures can be evaluated based on their cost and potential crash reduction.

In the realm of SPFs, there is ongoing research for intersection-related crashes on Virginia highways being conducted by Garber and Rivera (2008). Their work is also based heavily on SafetyAnalyst and intended for use across the state. Findings from their research, in conjunction with the SPFs presented here, provide the ability for analysis of two-lane segments and intersections.

Research has also been conducted in Virginia by Garber and Ehrhart (2000) to determine the effect of different variables on crash rates based on highway type. This study established that there is a relationship between crash rates and independent variables of standard deviation of speed, mean speed, and flow per lane. Garber and Ehrhart's recommendations for future research included using stochastic models, not assuming that crash rates are linear with respect to changes in flow per lane. These recommendations are addressed in the development of SPFs for Virginia two-lane highways conducted in this study. This work, which is specific to Virginia's characteristics, is useful in determining which traffic and geometric factors may have an effect on crashes and should be considered for inclusion in the SPFs. The preceding Virginia work serves to illustrate where the need for SPFs comes from and their use in relation to past and future research.

Evaluation of Existing Models

Each of the two-lane interim SPFs created in the development of SafetyAnalyst was evaluated for its transferability to the data collected on Virginia two-lane roads using two methods (visual comparison of plots and their R_{FT}^2 values). The SPFs were compared graphically to the collected Virginia data. An example of this comparison is shown for rural and urban roads in Figures 7 and 8, respectively.

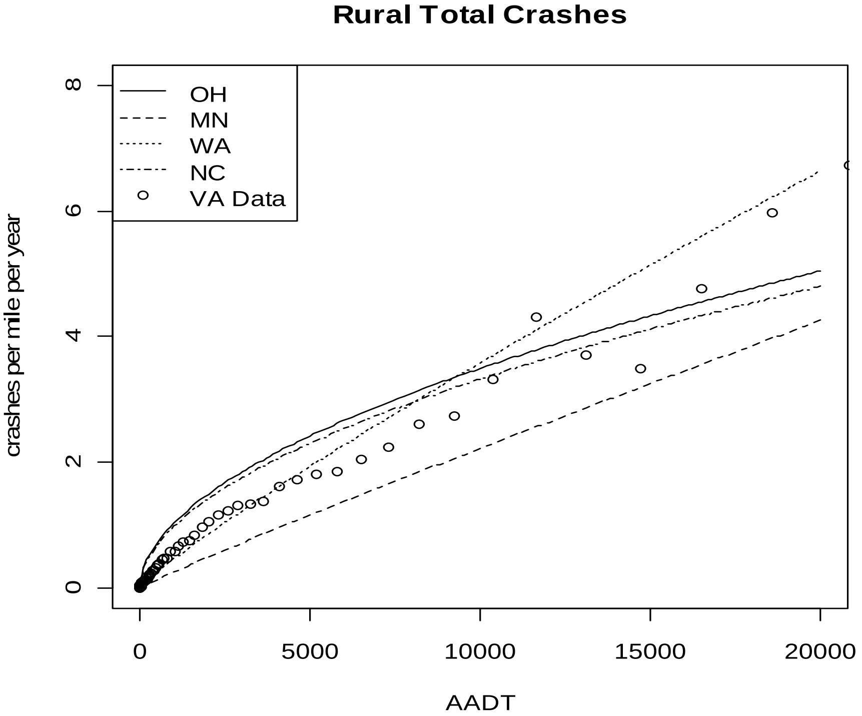

Figure 7. Rural Two-lane Virginia Aggregated Data Compared to SafetyAnalyst Interim SPFs

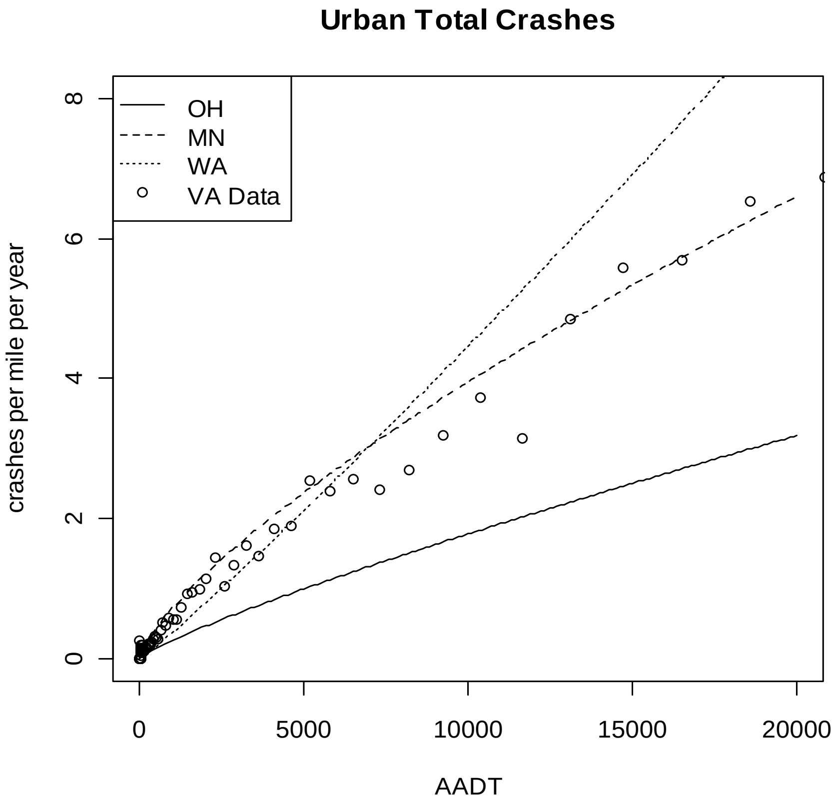

Figure 8. Urban Aggregated Virginia Data Compared to SafetyAnalyst Interim SPFs

Based on Figures 7 and 8, it is evident that none of the SafetyAnalyst interim SPFs provides a good fit to the Virginia data over the AADT range. Models from different states appear to provide a better fit across different volume ranges. For example, at low urban volumes (AADT < 5000), the Minnesota model best fits the Virginia data whereas at low rural volumes, the Washington model best fits the Virginia data. At medium-range urban volumes (5000 < AADT ≥ 12,000), none seems to fit the Virginia data. The Ohio models selected for use in SafetyAnalyst do not fit the Virginia rural or urban data. Probable reasons for these discrepancies include differences that may exist between the roadside environments of Virginia and the other states and differences that may exist between crash and AADT reporting thresholds among the different states.

In addition to the graphical comparison, the coefficient of determination, R^2, and the Freeman-Tukey R^2 (R_{FT}^2) coefficient were calculated to test the fit of these SPFs to Virginia's roads using all of the statewide data. Tables 5 and 6 show these calculated values for both total crashes and the combined fatal and injury crashes for rural and urban roads.

Table 5. Fit of Virginia Total Crashes to SafetyAnalyst SPFs

	Rural Total Crashes				Urban Total Crashes		
	OH	**MN**	**WA**	**NC**	**OH**	**MN**	**WA**
R^2	0.35627	0.28727	0.48740	0.38128	-0.16281	0.33297	0.43931
R_{FT}^2	0.32400	0.14847	0.41205	0.35430	-0.34127	0.36350	0.36593

Table 6 . Fit of Virginia Fatal and Injury Crashes to SafetyAnalyst SPFs

	Rural Fatal and Injury Crashes				Urban Fatal and Injury Crashes		
	OH	**MN**	**WA**	**NC**	**OH**	**MN**	**WA**
R^2	0.30445	0.11126	0.35800	0.30195	-0.30181	0.14172	0.36624
R_{FT}^2	0.28448	0.00662	0.29527	0.29064	-0.68170	0.02195	0.23485

Across Tables 5 and 6, the R^2 and R_{FT}^2 values for each SPF are fairly similar. Regardless of which measure of goodness of fit is examined, the ordered ranking of which models fit best does not change. The negative R^2 and R_{FT}^2 values are possible because these calculations were not performed on the same data points used to create the models (Miller, 2005). For each of the four characteristic and crash combinations, between rural or urban location and total or fatal plus injury crashes, the SPF developed with Washington data provides the best fit to Virginia data. It is interesting to note that the urban Washington SPFs show a better fit to the Virginia data, with an R_{FT}^2 of 36.6% for total crashes and 23.5% for fatal and injury crashes, than to the Washington data for which they were developed, with an R_{FT}^2 of 19.2% for total crashes and 22.2% for fatal and injury crashes (see Table 4), suggesting that exposure explains a higher percentage of the crashes in Virginia than in Washington.

The SPFs selected for use in SafetyAnalyst were the Ohio models, for the rural and urban conditions (Harwood et al., 2004). It is evident based on Tables 5 and 6 that the use of the Ohio models, although possibly adequate for rural roads, is not at all transferable for urban locations. For both conditions, it is plainly evident that the Ohio SPFs can be improved upon with respect to Virginia conditions, and there are even options among the other interim models that would be better candidates.

The development of each of these interim SPFs for SafetyAnalyst did not include data from Virginia highways. It is therefore not surprising that they do not show high R^2 values when applied to Virginia. With the implementation of the yearly calibration factor, c_y, defined in Equation 9 and shown in use in Equation 8, it is likely that the fit of these SPFs to the Virginia data could improve, but this will only change the intercept for each model and would not take the full impact of the AADT into consideration as its AADT exponent (β) will not change. This action, therefore, does not produce SPFs for use in Virginia that will be as accurate as those developed using Virginia data. This examination of the transferability of the SafetyAnalyst interim SPFs to Virginia's two-lane highways illustrates why the development of models specifically for Virginia is necessary.

GLM Results

GLM was used to develop SPFs for each of the 72 model cases, 36 models for total crashes and 36 for fatal plus injury crashes. This tree of 72 models was further pruned to a total of 36 models. Each model takes the same model form used in SafetyAnalyst, which is displayed in Equation 1.

P-values for both model coefficients were less than 0.001 in all cases, indicating that both the *a* and *b* coefficients were significant in the model.

The model conditions that directly relate to what has been developed and is used in SafetyAnalyst are simply a split by rural or urban location and total or fatal plus injury crashes. The four SPFs that cover Virginia are shown in Table 7 and were developed using a 70% sample of available Virginia data. The Virginia-specific SPFs show a better fit to the Virginia data than their Ohio counterparts suggested in SafetyAnalyst, as shown in Table 7. Figures 9 through 12 illustrate how the SPFs developed based on Virginia data compared to the SafetyAnalyst interim SPFs.

Table 7. Virginia Statewide Rural and Urban SPF Results

	a		*b*				R_{FT}^2 using 70% VA data	
	Value	**Standard Error**	**Value**	**Standard Error**	**Sample Size**[a]	**MSPE 30%**	**VA SPF**	**OH SPF**
Total Rural Crashes	-5.710	0.0313	0.744	0.0045	287107	23%	34%	10%
Fatal and Injury Rural Crashes	-6.462	0.0407	0.731	0.0058	287107	9%	21%	17%
Total Urban Crashes	-6.105	0.1055	0.803	0.0133	201618	15%	35%	31%
Fatal and Injury Urban Crashes	-7.640	0.1498	0.863	0.0179	201618	4%	23%	18%

[a]Sample size is the number of sites germane to this model multiplied by the number of years in the study period.

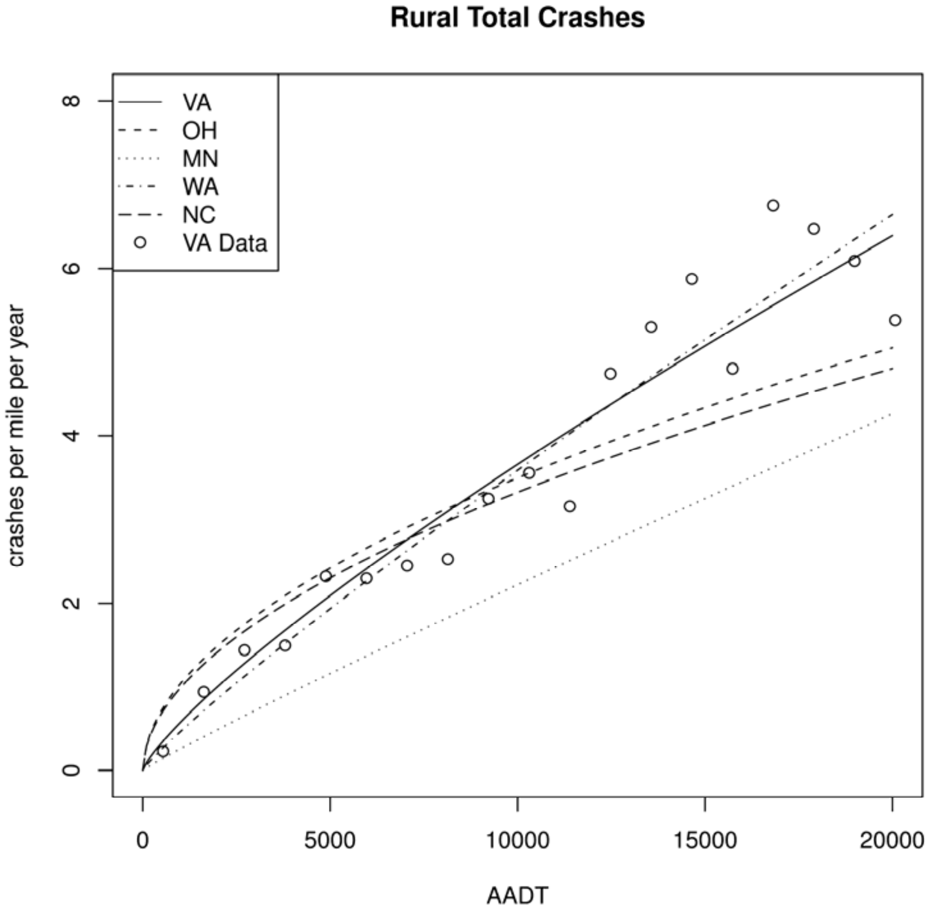

Figure 9. Comparison of Virginia-Specific SPF for Rural Total Crashes with Corresponding SafetyAnalyst SPFs

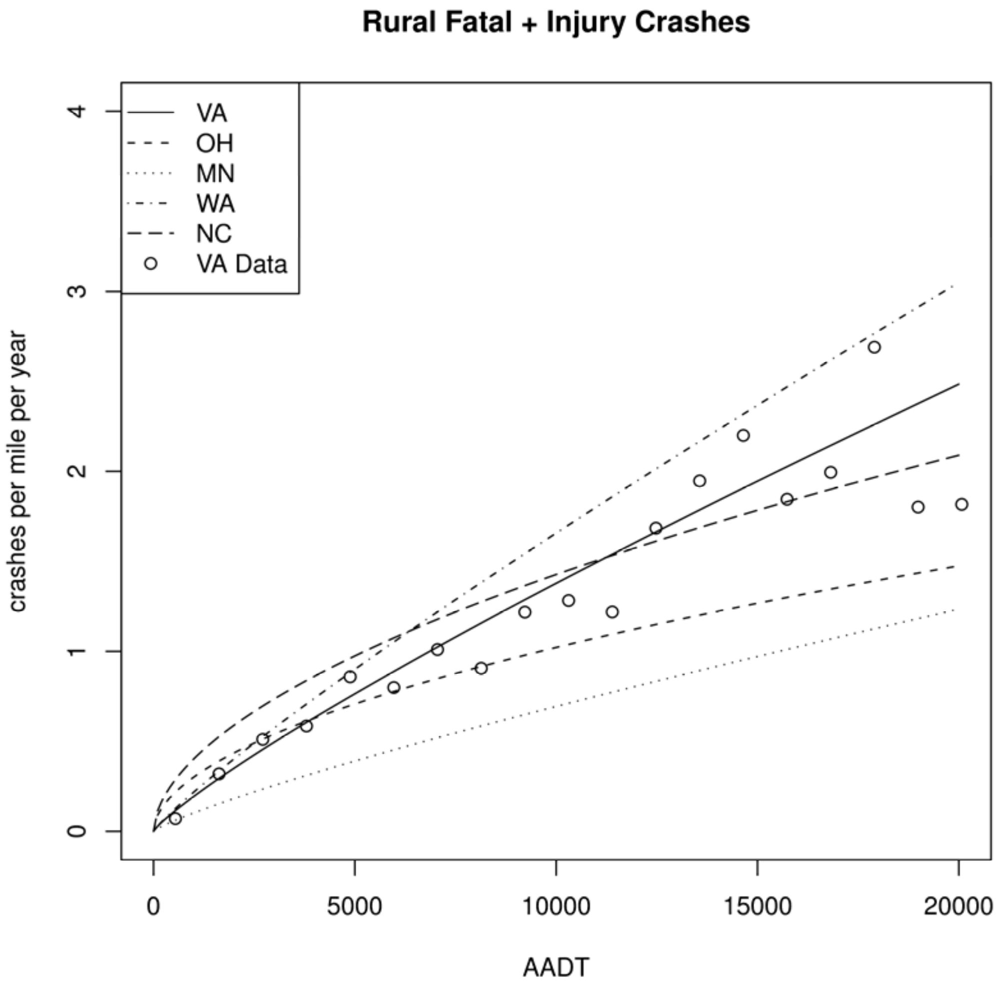

Figure 10. Comparison of Virginia-Specific SPF for Rural Fatal and Injury Crashes with Corresponding SafetyAnalyst SPFs

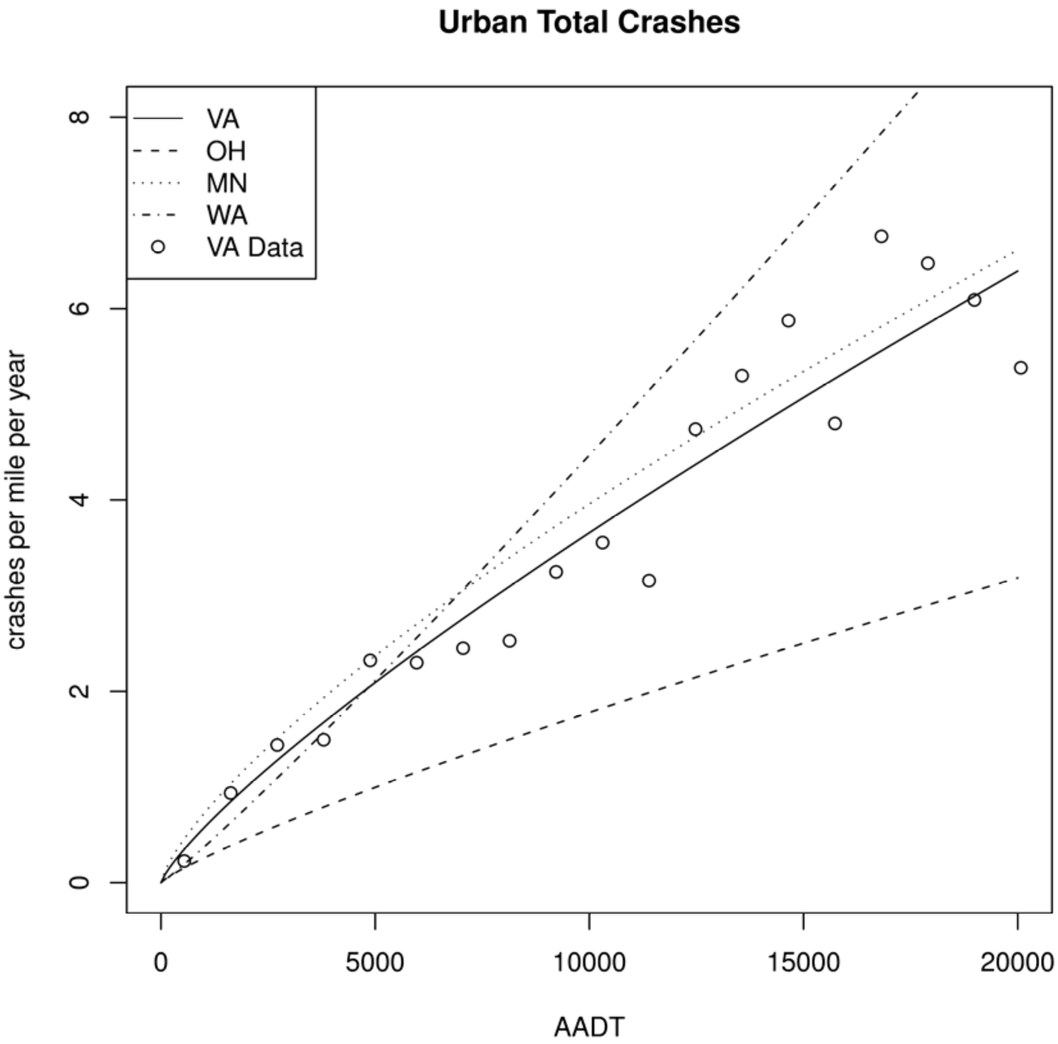

Figure 11. Comparison of Virginia-Specific SPF for Urban Total Crashes with Corresponding SafetyAnalyst SPFs

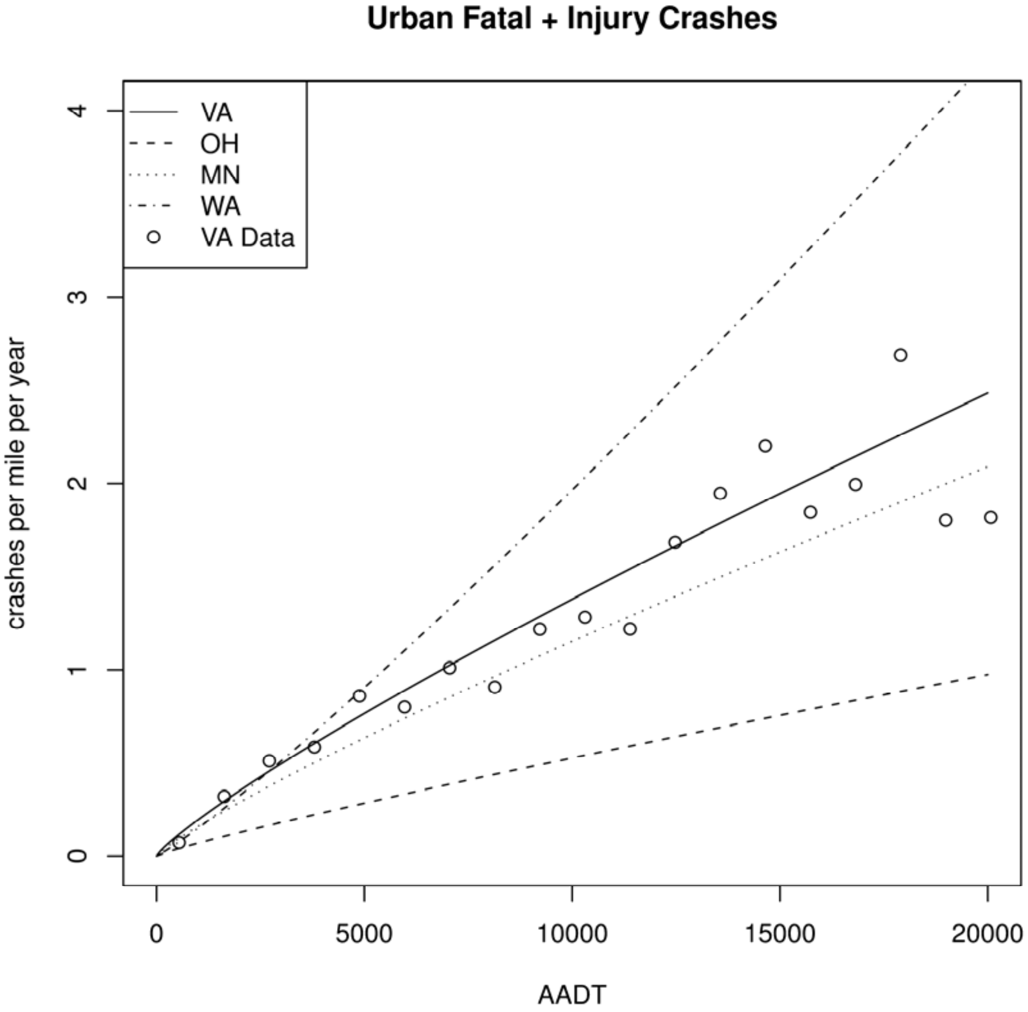

Figure 12. Comparison of Virginia-Specific SPF for Urban Fatal and Injury Crashes with Corresponding SafetyAnalyst SPFs

It is evident from Figures 9 through 12 that the Virginia SPFs take a somewhat similar shape to each of the SafetyAnalyst interim models while still providing a different fit. The greatest resemblance is in the rural total crashes condition, where the Virginia SPF is comparable to the Washington model but predicting slightly higher crash totals at lower volumes and slightly lower crash totals at higher volumes. These four broader SPFs developed for Virginia fulfill the requirements of SafetyAnalyst and can be applied within the state.

Although these four SPFs are all that are currently used for SafetyAnalyst across other states, further efforts were made to attempt to improve on the estimating capabilities of these models by further dividing the sites based on their characteristics. The first division investigated was a split into primary and secondary roads. The resulting SPFs and their fit to the Virginia data can be seen in Table 8.

Table 8. Statewide SPFs by Classification

		a		*b*			R_{FT}^2 using 70% VA data	
		Value	**Standard Error**	**Value**	**Standard Error**	**Number of Sites**	**VA SPF**	**OH SPF**
Total Crashes	Rural	-5.709	0.031	0.744	0.005	287107	34%	10%
	Rural Primary	-5.123	0.124	0.666	0.015	43194	40%	27%
	Rural Secondary	-6.002	0.042	0.794	0.007	243912	30%	-2%
	Urban	-6.105	0.106	0.803	0.013	201618	35%	31%
	Urban Primary	-7.091	0.543	0.938	0.060	6101	30%	25%
	Urban Secondary	-5.943	0.120	0.779	0.016	195517	34%	30%
Fatal and Injury Crashes	Rural	-6.462	0.041	0.731	0.006	287107	21%	17%
	Rural Primary	-5.393	0.162	0.591	0.020	43194	24%	23%
	Rural Secondary	-6.844	0.054	0.797	0.008	243912	17%	12%
	Urban	-7.640	0.150	0.863	0.018	201618	23%	18%
	Urban Primary	-7.711	0.620	0.899	0.068	6101	18%	12%
	Urban Secondary	-7.391	0.158	0.830	0.019	195517	23%	18%

In splitting the sites into primary and secondary routes, the model fit generally improved for the rural primary routes based on the R_{FT}^2. Other routes failed to show improvement in model fit over the combined case. Further SPFs split by classification for each of the geographic regions can be seen in Tables A-1 and A-2 of Appendix A.

The next site breakdown for further analysis was by geographic region. As previously discussed, Virginia was divided into three regions: Northern, Western, and Eastern. SPFs were then developed for each of these regions where possible. There were not enough sites in the Western Region to develop separate models for urban primary and urban secondary roads. The complete models can also be seen in Tables A-1 and A-2 of Appendix A, and a comparison of the overall rural and urban SPFs for each geographic region to the statewide SPFs is shown in Tables 9 and 10.

Table 9. Total Crash SPFs by Geographic Region

		a		*b*			R_{FT}^2 using 70% VA data	
Fatal and Injury Crashes		**Value**	**Standard Error**	**Value**	**Standard Error**	**Number of Sites**	**VA SPF**	**OH SPF**
Rural	Statewide	-5.709	0.031	0.744	0.005	287107	34%	10%
	Northern	-5.568	0.085	0.739	0.011	28652	45%	35%
	Western	-5.681	0.039	0.747	0.006	174081	33%	10%
	Eastern	-5.709	0.066	0.721	0.010	84375	31%	-8%
Urban	Statewide	-6.105	0.106	0.803	0.013	201618	35%	31%
	Northern	-5.995	0.155	0.799	0.020	107399	35%	32%
	Western	-6.130	0.210	0.814	0.027	31998	38%	32%
	Eastern	-6.450	0.208	0.827	0.026	62224	32%	30%

Table 10. Fatal and Injury Crash SPFs by Geographic Region

Fatal and Injury Crashes		*a*		*b*		Number of Sites	R_{FT}^2 using 70% VA data	
		Value	Standard Error	Value	Standard Error		VA SPF	OH SPF
Rural	Statewide	-6.462	0.041	0.731	0.006	287107	21%	17%
	Northern	-6.622	0.116	0.745	0.015	28652	27%	25%
	Western	-6.483	0.052	0.741	0.007	174081	20%	16%
	Eastern	-6.404	0.086	0.705	0.012	84375	18%	12%
Urban	Statewide	-7.640	0.150	0.863	0.018	201618	23%	18%
	Northern	-7.865	0.218	0.890	0.026	107399	23%	19%
	Western	-7.073	0.274	0.813	0.034	31998	23%	16%
	Eastern	-7.657	0.261	0.854	0.031	62224	20%	16%

Model Pruning Results

Tables A-1 and A-2 of Appendix A give the full model tree for all 72 SPFs. The pruning algorithm identified 36 specific models that are not redundant compared to their more general counterpart, with 26 of these being for urban and rural intersections separately. The specificity could be either for regions or primary versus secondary facility types. The models pruned are also identified in Tables A-1 and A-2 as "TRUE." The pruned set of models was similar for total crashes and fatal plus injury crashes but not identical, indicating that these pruned SPFs are for crash types that have similar AADT exponents for different areas of the modeling space than others. The recommended SPFs for urban and rural roads separately for use in Virginia are given in Tables 11 and 12. The complete set of 36 non-redundant SPFs is given in Tables A-3 and A-4 of Appendix A The models for rural and urban roads combined are also included in Tables A-3 and A-4 of Appendix A to allow for any analysis that may involve rural and urban roads combined. In general, the models for rural and urban roads separately are preferable to the combined models.

Table 11. Recommended SPFs for Total Crashes[a]

Urban/Rural	Region	Primary/Secondary	a	b	k	Rsqft	MSPE
Rural	All	Secondary	-6.002	0.794	0.423	30%	0.171
Rural	All	Primary	-5.123	0.666	0.351	40%	0.567
Rural	All	All	-5.709	0.744	0.400	34%	0.229
Rural	East	Secondary	-6.091	0.788	0.481	28%	0.139
Rural	East	Primary	-5.351	0.663	0.311	36%	0.374
Rural	East	All	-5.709	0.721	0.419	31%	0.183
Rural	North	Secondary	-6.013	0.808	0.307	40%	0.262
Rural	North	Primary	-5.163	0.686	0.299	46%	1.229
Rural	North	All	-5.568	0.739	0.334	45%	0.361
Urban	All	Secondary	-5.943	0.779	1.234	34%	0.121
Urban	All	Primary	-7.091	0.938	0.880	30%	1.073
Urban	All	All	-6.105	0.803	1.128	35%	0.155
Urban	East	Primary	-7.491	0.990	0.926	18%	1.184
Urban	West	Primary	-7.443	0.975	0.958	38%	0.497
Urban	West	All	-6.130	0.814	0.710	38%	0.141

[a] For segment categories not included in this table, see Table A-3 in Appendix A.

Table 12. Recommended SPFs for Fatal Plus Injury Crashes[a]

Urban/Rural	Region	Primary/Secondary	a	b	k	Rsqft	MSPE
Rural	All	Secondary	-6.844	0.797	0.429	17%	0.065
Rural	All	Primary	-5.393	0.591	0.379	24%	0.207
Rural	All	All	-6.462	0.731	0.436	21%	0.086
Rural	East	Primary	-6.363	0.686	0.387	22%	0.137
Rural	North	Secondary	-7.174	0.837	0.399	25%	0.087
Rural	North	Primary	-5.861	0.648	0.437	27%	0.367
Urban	All	Secondary	-7.391	0.830	1.117	23%	0.027
Urban	All	Primary	-7.711	0.899	0.735	18%	0.256
Urban	All	All	-7.640	0.863	1.080	23%	0.035
Urban	West	Primary	-7.668	0.896	0.825	27%	0.158
Urban	West	All	-7.073	0.813	0.758	23%	0.043

[a] For segment categories not included in this table, see Table A-4 in Appendix A.

Site Prioritization Results

Using the procedure outlined in the "Methods" section, a sample data set of eight selected sites were prioritized based on their crash history and PSI. The two methods compared were ranking by crash rates and ranking by the EB method using SPFs. The selected sites and their prioritization based on each method are shown in Table 13.

It is clear from Table 13 that even among only these eight sample sites, using the EB method of site prioritization with SPFs yields much different results than ranking simply by crash rate. These results take into account the expected safety performance for each site, thereby identifying those sites that have the highest PSI when appropriate safety countermeasures are implemented.

Also using the procedure described in the "Methods" section, the top 10 sites from each of the two randomly selected VDOT districts (Culpeper and Staunton) were obtained based on the PSI using the EB and crash rates methods. The results are shown in Tables 14 and 15 for the Culpeper District and in Tables 16 and 17 for the Staunton District. These results clearly indicate the superiority of the EB method. For example, using the EB method, the total PSI for

Table 13. Sample Site Prioritization Results

Site			Crash Rate Method		Empirical Bayes Method	
Route	Start MP	End MP	Crash Rate[a]	Ranking	Potential for Safety Improvement (PSI) Crashes/yr[b]	Ranking
30-858	0.00	0.10	23430	1	0.05	3
02-1015	0.31	0.56	1773	3	0.04	4
30-1240	0.13	0.38	1569	5	0.08	1
23-700	0.00	0.16	1121	6	0.06	2
23-729	5.99	6.24	997	7	0.27	8
78-626	11.82	12.07	950	8	0.04	5
54-665	0.88	1.13	4778	2	0.04	6
32-632	0.00	0.25	1605	4	0.03	7

[a] Crashes/1 million VMT.

[b] Difference between the EB long-term estimated crashes and the number of crashes predicted by the SPF.

Table14. Ranking by EB Method for District 7 (Culpeper District)

Rank	Site			Potential for Safety Improvement (PSI) crashes/yr [a]
	Route Number	Start MP	End MP	
1	SR 22	24.66	24.91	1.07
2	02-631	11.40	11.65	0.94
3	02-631	11.65	11.90	0.94
4	US-250	91.71	91.96	0.89
5	SR-20	44.00	44.25	0.85
6	02-631	11.90	12.15	0.65
7	SR-20	43.75	44.00	0.61
8	US-15	111.80	112.85	0.59
9	US-15	144.44	144.69	0.51
10	23-729	5.99	6.24	0.46

[a] Difference between the EB long-term estimated crashes and the number of crashes predicted by the safety performance function.. Sum of PSIs = 7.51crashes/yr.

Table 15. Ranking by Crash Rate for District 7 (Culpeper District)

Rank	Crash Rate[a]	Site			Potential for Safety Improvement (PSI) Crashes/yr[b]
		Route	Start MP	End MP	
1	23430	30-858	0.00	0.10	0.05
2	4778	54-665	0.88	1.13	0.04
3	1773	02-1015	0.31	0.56	0.04
4	1605	32-632	0.00	0.25	0.03
5	1569	30-1240	0.13	0.38	0.08
6	1372	23-621	8.70	9.00	0.07
7	1121	23-700	0.00	0.16	0.06
8	1044	30-738	3.19	3.44	0.07
9	997	23-729	5.99	6.24	0.27
10	950	78-626	1.82	2.07	0.04

[a] Crash Rate =number of crashes per 100,000,vehicle miles traveled.

[b] Difference between the EB long-term estimated crashes and the number of crashes predicted by the safety performance function. Sum of PSIs = 0.71 crash/yr.

Table 16. Ranking by EB Method for District 8 (Staunton District)

Rank	Site			Potential for Safety Improvement (PSI) Crashes/yr[a]
	Rte Number	Start MP	End MP	
1	US-11	325.77	326.02	1.37
2	34-622	12.46	12.65	0.83
3	US-11	202.94	203.22	0.79
4	US-11	325.52	325.77	0.74
5	US 11	202.69	202.94	0.65
6	US-11	300.16	300.41	0.61
7	SR- 42	271.03	271.29	0.46
8	SR-130	0.06	0.31	0.45
9	07-608	27.85	28.10	0.30
10	SR-285	0.15	0.4	0.28

[a] Difference between the EB long-term estimated crashes and the number of crashes predicted by the safety performance function. Sum of PSIs = 6.48 crashes/yr.

Table 17. Ranking by Crash Rates for District 8 (Staunton District)

Rank	Crash Rate[a]	Site			Potential for Safety Improvement (PSI) Crashes/yr[b]
		Route	Start MP	End MP	
1	84408	81-1102	0.00	0.25	0.02
2	15078	07-2002	0.00	0.09	0.02
3	7565	34-1254	0.00	0.16	0.02
4	4183	34-1070	0.38	0.63	0.07
5	2665	81-793	0.19	0.44	0.04
6	2164	03-631	0.00	0.08	0.06
7	2049	82-644	5.31	5.56	0.21
8	1932	93-611	4.81	5.06	0.06
9	1894	81-743	0.56	0.81	0.02
10	1771	07-1925	0.19	0.44	0.03

[a] Crash Rate = crashes per 100,000,000 vehicles miles traveled.

[b] Difference between the EB long-term estimated crashes and the number of crashes predicted by the safety performance function. Sum of PSIs = 0.55 crash/yr.

the top 10 sites in the Culpeper District was 7.51 crashes/yr; that based on the crash rates was only 0.71 crash/yr. Similarly, the PSI for the top 10 sites in the Staunton District based on the EB method was 6.48 crashes/yr, whereas that based on the crash rates was only 0.55 crash/yr.

Using the prioritization procedure, the top 50 sites in each district were identified based on the fatal and injury crashes and are given in Tables B-1 and B-2 of Appendix B.

Study Limitations

Despite the best efforts of the researchers to fit the data to statistical models, possible limitations could have been introduced. The most likely sources of problems are human error, errors in the databases used, and assumptions made for this study.

There was a potential for error was in the site selection process. Sites were originally selected based on each district's proportion of two-lane mileage; however, because of missing information that caused some sites to be removed, as well as the intent to include a larger number of urban sites, the final list of sites did not exactly follow the two-lane mileage proportions. Additional possible sources of error were in the counting of the number of intersections within each site. This task was performed with a combination of visual tools, such as Google Maps and VDOT's GIS Integrator, and roadway databases, introducing the chance for human error. Data collected from VDOT databases included AADT and crash data. It is possible that AADT could have been improperly collected, normalized, or estimated from previous counts for any given site, but particularly for the lower volume secondary routes. Potential errors in the crash database also include the misreporting of crash location. As each site was less than 1 mi in length and included the elimination of 0.03 mi on each side of an intersection, crashes that were recorded at the wrong location may have been assigned to an incorrect site for this study. This source of error could increase or decrease the recorded number of crashes from the total that actually occurred. These unknowns cannot be accounted for in the SPFs developed.

Although each of these potential sources of error exists, it is unlikely that the overall findings were significantly impacted. With a total of 139,635 sites used, errors in a number of sites could be absorbed without any noticeable change to the resulting SPFs. In addition, none of the possible error sources should result in a dramatic change in any of the data.

CONCLUSIONS

- *The development of SPFs specifically for Virginia is necessary, as the existing models suggested in SafetyAnalyst do not adequately describe Virginia's characteristics.* The fit in terms of the R_{Ft}^2 values of the Virginia-specific models and the suggested Ohio models as shown in Table 8 indicates that the Virginia-specific SPFs in general fit the Virginia data better than do the Ohio SPFs. Virginia's unique topography, combination of heavily rural and heavily urban regions, and vast network of state-maintained secondary roads all contribute to the distinctive set of attributes that highlight the need for Virginia-specific SPFs.

- *The site aggregation into geographical regions and the classification of the two-lane roads into rural primary, rural secondary, urban primary, and urban secondary have the potential to improve the fit of the SPFs.* These divisions group sites with similar roadway characteristics and driver expectations, which in some cases tended to improve model fit. For example, the goodness of fit improvement for specific geographic regions can be observed in the SPFs for total crashes on rural roads, where the R_{FT}^2 for the statewide SPF is 0.34, which improved to 0.45 for the Northern Region. In addition, these divisions highlight the weaknesses of a broader model so that they can be addressed in future research.

- *The use of the EB method with the appropriate SPFs identifies sites with a high PSI in contrast to the use of crash rates, which assumes a one-to-one relationship between crashes and AADT.* The results of the site prioritization analysis demonstrate the efficacy of using the EB method and the appropriate SPFs for identifying sites for safety improvement.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division should use SPFs developed specifically for Virginia when using SafetyAnalyst for the screening and prioritization of sites for safety improvement.* The results of this study clearly indicate that SPFs specifically developed for Virginia tend to give a better fit to the Virginia data than the suggested SafetyAnalyst Ohio SPFs.

2. *VDOT's Traffic Engineering Division should analyze urban and rural two-lane segments separately, using the appropriate SPFs given in Tables 11 and 12.* The geometric and operational characteristics of urban and rural two-lane segments are not the same, and these are reflected in the different SPFs. This is also in keeping with the suggested approach given in the *SafetyAnalyst User's Manual* (ITT Corporation, 2008).

3. *In the implementation of Recommendations 1 and 2, VDOT's Traffic Engineering Division should analyze the three geographic regions separately using the appropriate SPFs as soon as provision is made in SafetyAnalyst to do so.* Regional analysis will facilitate the use of specific regional SPFs that are included in the final recommended set of SPFs in Tables 11 and 12.

4. *In the implementation of Recommendations 1 and 2, VDOT's Traffic Engineering Division should analyze primary and secondary routes separately using the SPFs as soon as provision is made in SafetyAnalyst to do so.* The consideration of primary and secondary routes separately will facilitate the use of specific primary and secondary route SPFs given in the final recommended list of SPFs in Tables 11 and 12. The study results indicate that specific primary and secondary SPFs listed in the final set of recommended SPFs give less MSPEs than do the statewide SPFs.

BENEFITS AND IMPLEMENTATION PROSPECTS

Significant benefits will be accrued by the use of the Virginia-specific SPFs developed in this study. This is clearly illustrated in two ways. First, in examining the transferability of the suggested SPFs in SafetyAnalyst, it is clear these SPFs do not fit the Virginia data very well. The results of this study indicate that the Virginia-specific SPFs developed in this study fit the Virginia data much better than the suggested SafetyAnalyst SPFs. Second, the availability of the Virginia-specific SPFs will enhance the use of the EB method given in Safety Analyst for prioritizing sites for safety improvements. The study has also shown that the EB method better identifies sites with higher potential for crash reduction than those identified by crash rates.

The prospects for implementation of the study recommendations are very high as the study was requested by the Safety Section of VDOT's Traffic Engineering Division, which is planning to use the tools given in SafetyAnalyst, and an important requirement for this is the availability of suitable SPFs, which were developed in this study.

RECOMMENDATIONS FOR FUTURE RESEARCH

This research developed SPFs for two-lane highways in Virginia; however, in the process, it drew attention to future possibilities for improvement and expansion. For example, a future study could seek to increase the number of sites studied in developing the SPFs. This could potentially improve the results and also increase the depth of the model divisions, specifically among urban locations. In the development of SPFs, additional research is needed to investigate the inclusion of added independent variables, as more variables may improve the predictive capabilities of these models. Factors such as shoulder width, lane width, number of intersections, and number of driveways may all have important impacts on the number of crashes, yet they are unaccounted for in the current SPFs. It may also be useful to study the effect of reorganizing the regions differently than in this study, e.g., placing the Culpeper District in the Eastern Region rather than in the Northern Region on the regional SPFs. Last, the scope of this study was limited to state-maintained highways in Virginia. Future research could include sites within Virginia maintained by cities and/or towns; this would serve to increase the number of available sites while still keeping the site characteristics specific to Virginia.

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APPENDIX A

PRUNED AND RECOMMENDED SAFETY PERFORMANCE FUNCTIONS

The form of the SPFs given in Tables A-1 through A-4 is:

$$\text{Crashes} = e^{a} \times \text{AADT}^{b}\ \text{SL}$$

where

Crashes = predicted crashes per year
AADT = average annual daily traffic (vehicles/day)
SL = segment length (miles)
a and b = regression parameters.

Other Nomenclature:

ase = standard error for a
bse = standard error for b
k = dispersion parameter of the SPF
kse = standard error for k
$R_{sq}ft =$ Freeman-Tukey R^2 coefficient for the Virginia SPFs using the 30% Virginia evaluation data
$R_{sq}ftOH =$ Freeman-Tukey R^2 coefficient of the Ohio SPFs using the 30% Virginia evaluation data
MSPE = mean squared predictive error for the Virginia SPFs based on the 30% Virginia evaluation data
n = number of study sites.

Table A-1. SPFs for Total Crashes

Urban/Rural	Region	Primary/Secondary	a	b	ase	Bse	k	kse	n	Rsqcor	Rsqft	RsqftOH	MSPE	Pruned[a]
All	All	Secondary	-5.952	0.784	0.044	0.007	0.638	0.016	439430	33%	32%	8%	0.138	FALSE
All	All	Primary	-5.804	0.757	0.134	0.016	0.409	0.017	49295	39%	38%	28%	0.648	FALSE
All	All	All	-5.873	0.770	0.034	0.005	0.544	0.012	488723	37%	35%	16%	0.198	FALSE
All	East	Secondary	-5.905	0.754	0.073	0.011	0.701	0.035	131888	31%	29%	-5%	0.107	TRUE
All	East	Primary	-7.720	0.967	0.330	0.040	0.550	0.042	14712	30%	30%	7%	0.520	FALSE
All	East	All	-5.950	0.759	0.065	0.009	0.639	0.027	146598	32%	32%	2%	0.155	FALSE
All	North	Secondary	-5.931	0.791	0.103	0.015	0.828	0.035	130845	38%	38%	31%	0.167	FALSE
All	North	Primary	-6.306	0.823	0.480	0.054	0.497	0.042	5206	42%	42%	41%	1.126	TRUE
All	North	All	-5.850	0.779	0.089	0.012	0.716	0.027	136049	41%	42%	36%	0.207	TRUE
All	West	Secondary	-5.880	0.780	0.051	0.008	0.469	0.021	176698	31%	28%	0%	0.153	TRUE
All	West	Primary	-5.128	0.678	0.156	0.019	0.349	0.021	29380	42%	40%	31%	0.570	TRUE
All	West	All	-5.721	0.753	0.039	0.006	0.397	0.015	206077	36%	34%	12%	0.228	TRUE
Rural	All	Secondary	-6.002	0.794	0.042	0.007	0.423	0.016	243912	34%	30%	-2%	0.171	FALSE
Rural	All	Primary	-5.123	0.666	0.124	0.015	0.351	0.017	43194	41%	40%	27%	0.567	FALSE
Rural	All	All	-5.709	0.744	0.031	0.005	0.400	0.012	287107	38%	34%	10%	0.229	FALSE
Rural	East	Secondary	-6.091	0.788	0.088	0.014	0.481	0.034	72378	30%	28%	-15%	0.139	FALSE
Rural	East	Primary	-5.351	0.663	0.299	0.037	0.311	0.038	11998	35%	36%	3%	0.374	FALSE
Rural	East	All	-5.709	0.721	0.066	0.010	0.419	0.026	84375	32%	31%	-8%	0.183	FALSE
Rural	North	Secondary	-6.013	0.808	0.118	0.017	0.307	0.034	24669	48%	40%	24%	0.262	FALSE
Rural	North	Primary	-5.163	0.686	0.408	0.046	0.299	0.039	3984	49%	46%	42%	1.229	FALSE
Rural	North	All	-5.568	0.739	0.085	0.011	0.334	0.026	28652	48%	45%	35%	0.361	FALSE
Rural	West	Secondary	-5.877	0.779	0.052	0.008	0.409	0.021	146868	30%	27%	-4%	0.175	TRUE
Rural	West	Primary	-4.874	0.646	0.148	0.019	0.309	0.021	27213	41%	39%	30%	0.559	TRUE
Rural	West	All	-5.681	0.747	0.039	0.006	0.378	0.015	174081	37%	33%	10%	0.231	TRUE
Urban	All	Secondary	-5.943	0.779	0.120	0.016	1.234	0.046	195517	32%	34%	30%	0.121	FALSE
Urban	All	Primary	-7.091	0.938	0.543	0.060	0.880	0.067	6101	32%	30%	25%	1.073	FALSE
Urban	All	All	-6.105	0.803	0.106	0.013	1.128	0.039	201618	33%	35%	31%	0.155	FALSE
Urban	East	Secondary	-5.572	0.701	0.195	0.025	1.353	0.103	59511	32%	31%	29%	0.080	TRUE
Urban	East	Primary	-7.491	0.990	0.728	0.082	0.926	0.103	2713	26%	18%	18%	1.184	FALSE
Urban	East	All	-6.450	0.827	0.208	0.026	1.252	0.080	62224	32%	32%	30%	0.124	TRUE
Urban	North	Secondary	-5.984	0.794	0.154	0.020	1.280	0.061	106177	31%	35%	32%	0.141	TRUE
Urban	North	Primary	-8.673	1.090	1.118	0.119	0.894	0.128	1223	29%	25%	26%	1.682	TRUE
Urban	North	All	-5.995	0.799	0.155	0.020	1.294	0.058	107399	32%	35%	32%	0.150	TRUE

Urban/Rural	**Region**	**Primary/Secondary**	**a**	**b**	**ase**	**Bse**	**k**	**kse**	**n**	**Rsqcor**	**Rsqft**	**RsqftOH**	**MSPE**	**Pruned[a]**
Urban	West	Secondary	-5.884	0.783	0.219	0.029	0.666	0.080	29831	40%	35%	29%	0.101	TRUE
Urban	West	Primary	-7.443	0.975	1.294	0.144	0.958	0.134	2168	39%	38%	29%	0.497	FALSE
Urban	West	All	-6.130	0.814	0.210	0.027	0.710	0.067	31998	41%	38%	32%	0.141	FALSE

[a] Models labeled as TRUE are pruned models.

Table A-2. SPFs for Fatal Plus Injury Crashes

Urban/Rural	Region	Primary/Secondary	a	b	ase	bse	k	kse	n	Rsqcor	Rsqft	RsqftOH	MSPE	Pruned[a]
All	All	Secondary	-6.703	0.765	0.048	0.007	0.606	0.030	439430	22%	19%	15%	0.049	FALSE
All	All	Primary	-6.162	0.691	0.172	0.021	0.474	0.034	49295	24%	23%	23%	0.202	FALSE
All	All	All	-6.563	0.742	0.041	0.006	0.542	0.023	488723	23%	21%	19%	0.067	FALSE
All	East	Secondary	-6.421	0.707	0.089	0.013	0.650	0.063	131888	18%	17%	11%	0.040	TRUE
All	East	Primary	-8.134	0.913	0.377	0.045	0.519	0.076	14712	20%	19%	16%	0.160	FALSE
All	East	All	-6.545	0.726	0.079	0.011	0.543	0.047	146598	20%	19%	14%	0.053	TRUE
All	North	Secondary	-7.212	0.824	0.126	0.017	0.902	0.070	130845	27%	25%	23%	0.042	TRUE
All	North	Primary	-6.842	0.766	0.694	0.077	0.586	0.085	5206	24%	25%	26%	0.312	TRUE
All	North	All	-7.036	0.799	0.106	0.013	0.712	0.052	136049	27%	27%	26%	0.057	TRUE
All	West	Secondary	-6.647	0.769	0.065	0.010	0.486	0.040	176698	18%	16%	12%	0.059	TRUE
All	West	Primary	-5.518	0.620	0.195	0.024	0.370	0.041	29380	25%	24%	24%	0.204	TRUE
All	West	All	-6.468	0.739	0.050	0.007	0.432	0.029	206077	23%	20%	17%	0.083	TRUE
Rural	All	Secondary	-6.844	0.797	0.054	0.008	0.429	0.031	243912	21%	17%	12%	0.065	FALSE
Rural	All	Primary	-5.393	0.591	0.162	0.020	0.379	0.034	43194	25%	24%	23%	0.207	FALSE
Rural	All	All	-6.462	0.731	0.041	0.006	0.436	0.023	287107	23%	21%	17%	0.086	FALSE
Rural	East	Secondary	-6.866	0.787	0.113	0.018	0.431	0.062	72378	18%	16%	9%	0.058	TRUE
Rural	East	Primary	-6.363	0.686	0.408	0.050	0.387	0.078	11998	23%	22%	17%	0.137	FALSE
Rural	East	All	-6.404	0.705	0.086	0.012	0.450	0.050	84375	19%	18%	12%	0.071	TRUE
Rural	North	Secondary	-7.174	0.837	0.158	0.023	0.399	0.075	24669	32%	25%	21%	0.087	FALSE
Rural	North	Primary	-5.861	0.648	0.647	0.072	0.437	0.086	3984	26%	27%	28%	0.367	FALSE
Rural	North	All	-6.622	0.745	0.116	0.015	0.411	0.056	28652	28%	27%	25%	0.141	TRUE
Rural	West	Secondary	-6.717	0.783	0.070	0.011	0.457	0.041	146868	18%	16%	11%	0.064	TRUE
Rural	West	Primary	-5.294	0.590	0.191	0.024	0.325	0.040	27213	27%	25%	25%	0.198	TRUE
Rural	West	All	-6.483	0.741	0.052	0.007	0.427	0.030	174081	22%	20%	16%	0.088	TRUE
Urban	All	Secondary	-7.391	0.830	0.158	0.019	1.117	0.081	195517	23%	23%	18%	0.027	FALSE
Urban	All	Primary	-7.711	0.899	0.620	0.068	0.735	0.115	6101	21%	18%	12%	0.256	FALSE
Urban	All	All	-7.640	0.863	0.150	0.018	1.080	0.070	201618	23%	23%	18%	0.035	FALSE
Urban	East	Secondary	-6.895	0.735	0.268	0.033	1.222	0.192	59511	20%	18%	15%	0.023	TRUE
Urban	East	Primary	-8.861	1.032	0.947	0.104	0.788	0.172	2713	18%	14%	9%	0.215	TRUE
Urban	East	All	-7.657	0.854	0.261	0.031	0.847	0.124	62224	21%	20%	16%	0.035	TRUE
Urban	North	Secondary	-7.932	0.896	0.209	0.025	1.121	0.105	106177	23%	24%	19%	0.036	TRUE
Urban	North	Primary	-9.825	1.111	1.581	0.166	1.047	0.257	1223	19%	14%	12%	0.233	TRUE
Urban	North	All	-7.865	0.890	0.218	0.026	1.231	0.103	107399	22%	23%	19%	0.035	TRUE

Urban/Rural	**Region**	**Primary/Secondary**	**a**	**b**	**ase**	**bse**	**k**	**kse**	**n**	**Rsqcor**	**Rsqft**	**RsqftOH**	**MSPE**	**Pruned**[a]
Urban	West	Secondary	-6.993	0.793	0.280	0.036	0.897	0.181	29831	20%	19%	13%	0.033	TRUE
Urban	West	Primary	-7.668	0.896	1.601	0.179	0.825	0.220	2168	31%	27%	15%	0.158	FALSE
Urban	West	All	-7.073	0.813	0.274	0.034	0.758	0.132	31998	27%	23%	16%	0.043	FALSE

[a] Models labeled as TRUE are pruned models.

Table A-3. Recommended SPFs for Total Crashes

Equation No.	Urban/Rural	Region	Primary/Secondary	a	b	k	Rsqft	MSPE
A-1	All	All	Secondary	-5.952	0.784	0.638	32%	0.138
A-2	All	All	Primary	-5.804	0.757	0.409	38%	0.648
A-3	All	All	All	-5.873	0.770	0.544	35%	0.198
*	All	East	Secondary	Use Eq. 1				
A-4	All	East	Primary	-7.720	0.967	0.550	30%	0.520
A-5	All	East	All	-5.950	0.759	0.639	32%	0.155
A-6	All	North	Secondary	-5.931	0.791	0.828	38%	0.167
*	All	North	Primary	Use Eq. A-2				
*	All	North	All	Use Eq. A-3				
*	All	West	Secondary	Use Eq. A-1				
*	All	West	Primary	Use Eq. A-2				
*	All	West	All	Use Eq. A-3				
A-7	Rural	All	Secondary	-6.002	0.794	0.423	30%	0.171
A-8	Rural	All	Primary	-5.123	0.666	0.351	40%	0.567
A-9	Rural	All	All	-5.709	0.744	0.400	34%	0.229
A-10	Rural	East	Secondary	-6.091	0.788	0.481	28%	0.139
A-11	Rural	East	Primary	-5.351	0.663	0.311	36%	0.374
A-12	Rural	East	All	-5.709	0.721	0.419	31%	0.183
A-13	Rural	North	Secondary	-6.013	0.808	0.307	40%	0.262
A-14	Rural	North	Primary	-5.163	0.686	0.299	46%	1.229
A-15	Rural	North	All	-5.568	0.739	0.334	45%	0.361
*	Rural	West	Secondary	Use Eq. A-7				
*	Rural	West	Primary	Use Eq. A-8				
*	Rural	West	All	Use Eq.A-9				
A-16	Urban	All	Secondary	-5.943	0.779	1.234	34%	0.121
A-17	Urban	All	Primary	-7.091	0.938	0.880	30%	1.073
A-18	Urban	All	All	-6.105	0.803	1.128	35%	0.155
*	Urban	East	Secondary	-5.572	0.701	1.353	31%	0.080
A-19	Urban	East	Primary	-7.491	0.990	0.926	18%	1.184
*	Urban	East	All	Use Eq. A-18				
*	Urban	North	Secondary	Use Eq. A-16				
*	Urban	North	Primary	Use Eq. A-17				
*	Urban	North	All	Use Eq. A-18				
*	Urban	West	Secondary	Use Eq. A-16				
A-20	Urban	West	Primary	-7.443	0.975	0.958	38%	0.497
A-21	Urban	West	All	-6.130	0.814	0.710	38%	0.141

*Specific models pruned.

Table A-4. Recommended SPFs for Fatal Plus Injury Crashes

Equation No.	Urban/Rural	Region	Primary/Secondary	a	B	k	Rsqft	MSPE
A-22	All	All	Secondary	-6.703	0.765	0.606	19%	0.049
A-23	All	All	Primary	-6.162	0.691	0.474	23%	0.202
A-24	All	All	All	-6.563	0.742	0.542	21%	0.067
*	All	East	Secondary	Use Eq. 22				
A-25	All	East	Primary	-8.134	0.913	0.519	19%	0.160
*	All	East	All	Use Eq. 24				
*	All	North	Secondary	Use Eq. A-22				
*	All	North	Primary	Use Eq. A-23				
*	All	North	All	Use Eq. A-24				
*	All	West	Secondary	Use Eq. A-22				
*	All	West	Primary	Use Eq. A-23				
*	All	West	All	Use Eq. A-24				
A-26	Rural	All	Secondary	-6.844	0.797	0.429	17%	0.065
A-27	Rural	All	Primary	-5.393	0.591	0.379	24%	0.207
A-28	Rural	All	All	-6.462	0.731	0.436	21%	0.086
*	Rural	East	Secondary	Use Eq. A-26				
A-29	Rural	East	Primary	-6.363	0.686	0.387	22%	0.137
*	Rural	East	All	Use Eq. A-28				
A-30	Rural	North	Secondary	-7.174	0.837	0.399	25%	0.087
A-31	Rural	North	Primary	-5.861	0.648	0.437	27%	0.367
*	Rural	North	All	Use Eq. A-28				
*	Rural	West	Secondary	Use Eq. A-26				
*	Rural	West	Primary	Use Eq. A-27				
*	Rural	West	All	Use Eq. A-28				
A-32	Urban	All	Secondary	-7.391	0.830	1.117	23%	0.027
A-33	Urban	All	Primary	-7.711	0.899	0.735	18%	0.256
A-34	Urban	All	All	-7.640	0.863	1.080	23%	0.035
*	Urban	East	Secondary	Use Eq. A-32				
*	Urban	East	Primary	Use Eq. A-33				
*	Urban	East	All	Use Eq. A-34				
*	Urban	North	Secondary	Use Eq. A-32				
*	Urban	North	Primary	Use Eq. A-33				
*	Urban	North	All	Use Eq. A-34				
*	Urban	West	Secondary	Use Eq. A-32				
A-35	Urban	West	Primary	-7.668	0.896	0.825	27%	0.158
A-36	Urban	West	All	-7.073	0.813	0.758	23%	0.043

*Specific models pruned.

APPENDIX B

SITES PRIORITIZATION BASED ON FATAL AND INJURY SAFETY PERFORMANCE FUNCTIONS

Table B-1. Bristol District (No. 1) Prioritization by Empirical Bayes Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	US-460	11.25	11.50	0.72
2	SR-80	26.38	26.63	0.64
3	95-647	0.56	0.81	0.64
4	95-647	0.50	0.75	0.64
5	95-647	0.63	0.88	0.64
6	95-647	0.69	0.94	0.64
7	US-460	11.31	11.57	0.61
8	US-460	11.19	11.44	0.61
9	95-647	0.75	1.00	0.58
10	SR-80	26.32	26.57	0.54
11	95-647	0.44	0.69	0.53
12	SR-63	2.88	3.13	0.49
13	SR-63	2.81	3.06	0.47
14	SR-80	26.44	26.69	0.46
15	SR-75	7.97	8.22	0.46
16	SR-75	7.91	8.16	0.46
17	SR-83	46.39	46.64	0.45
18	SR-75	8.04	8.29	0.45
19	US-58	92.99	93.24	0.43
20	US-58	93.05	93.30	0.43
21	US-58	93.11	93.36	0.43
22	95-647	0.38	0.63	0.42
23	US-460	7.06	7.31	0.42
24	US-460	7.13	7.38	0.42
25	SR-75	7.85	8.10	0.42
26	US-58	92.92	93.17	0.42
27	US-11	7.28	7.53	0.40
28	95-647	0.81	1.06	0.40
289	SR-67	10.75	11.00	0.40
30	US-11	7.34	7.59	0.39
31	SR-67	10.81	11.06	0.36
32	SR-72	41.49	41.74	0.35
33	SR-72	41.43	41.68	0.35
34	SR-67	10.69	10.94	0.34
35	SR-83	46.33	46.58	0.34
36	US-460	7.19	7.44	0.32
37	US-11	7.40	7.65	0.32
38	SR-80	26.26	26.51	0.32
39	SR-72	41.56	41.81	0.27
40	US-11	7.22	7.47	0.27
41	SR-67	10.63	10.88	0.25
42	SR-72	48.24	48.49	0.24
43	SR-72	48.18	48.43	0.22
44	SR-63	0.44	0.69	0.13
45	US-58	32.65	32.90	0.12
46	SR-63	0.38	0.63	0.12
47	US-58	32.71	32.96	0.11
48	SR-71	16.44	16.69	0.11
49	95-1712	0.25	0.50	0.11
50	SR-65	22.75	23.00	0.09

Table B-2. Salem District (No. 2) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	US-11	160.26	160.51	1.40
2	A1SR-57	2.92	3.17	1.12
3	US-11	160.20	160.45	1.10
4	US-11	160.33	160.58	1.03
5	A1SR-57	2.85	3.10	1.03
6	A1SR-57	2.98	3.23	1.00
7	SR-118	1.64	1.84	0.88
8	SR-40	36.56	36.81	0.79
9	US-219	1.44	1.73	0.77
10	A1SR-57	3.04	3.29	0.73
11	A1SR-57	2.79	3.04	0.70
12	SR-40	36.62	36.87	0.65
13	US-11	160.14	160.39	0.64
14	80-625	0.31	0.60	0.64
15	SR-40	36.49	36.74	0.64
16	US-11	160.39	160.64	0.62
17	US-221	91.27	91.56	0.61
18	SR-40	36.68	36.93	0.54
19	A1SR-57	3.10	3.35	0.53
20	US-221	91.15	91.40	0.52
21	US-221	91.21	91.46	0.52
22	80-625	0.25	0.50	0.50
23	44-687	2.86	3.11	0.49
24	US-220	96.58	96.83	0.49
25	SR-40	36.74	36.99	0.45
26	US-220	96.64	96.89	0.43
27	44-687	2.80	3.05	0.42
28	US-219	1.38	1.63	0.41
29	11-779	12.18	12.43	0.40
30	44-687	2.93	3.22	0.40
31	11 -779	12.25	12.50	0.39
32	US-11	138.20	138.45	0.36
33	SR-40	36.81	37.06	0.36
34	11-779	12.31	12.56	0.32
35	77-600	3.13	3.38	0.30
36	09-626	11.90	12.15	0.28
37	44-650	2.21	2.46	0.28
38	44-609	6.25	6.50	0.27
39	09-1425	0.25	0.50	0.24
40	SR-115	3.32	3.57	0.23
41	SR-115	3.26	3.51	0.22
42	US-11	160.45	160.70	0.19
43	11-779	12.37	12.62	0.19
44	SR-115	3.38	3.63	0.12
45	US-219	1.06	1.31	0.11
46	US-219	1.00	1.25	0.11
47	80-1567	0.00	0.25	0.09
48	US-219	1.13	1.38	0.08
49	80-1567	0.06	0.31	0.08
50	80-1567	0.13	0.38	0.02

Table B-3. Lynchburg District (No. 3) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	15-622	1.13	1.39	0.91
2	US-15	81.99	82.24	0.89
3	US-15	81.93	82.18	0.87
4	C6US-29	0.00	0.25	0.85
5	US-15	82.05	82.30	0.81
6	US-501	60.54	60.79	0.73
7	41-654	2.44	2.73	0.72
8	US-501	60.48	60.73	0.71
9	15-622	1.06	1.31	0.64
10	71-750	1.63	1.88	0.64
11	71-750	1.69	1.94	0.64
12	71-750	1.75	2.00	0.64
13	US-501	60.60	60.85	0.63
14	71-750	1.56	1.81	0.62
15	15-622	1.47	1.72	0.61
16	41-654	2.31	2.56	0.61
17	41-654	2.38	2.63	0.61
18	71-750	1.81	2.06	0.61
19	41-654	2.25	2.50	0.57
20	US-15	81.87	82.12	0.54
21	41-654	0.19	0.44	0.50
22	41-654	0.25	0.50	0.50
23	41-654	2.19	2.44	0.50
24	SR-151	27.19	27.44	0.46
25	71-750	1.50	1.75	0.46
26	71-750	1.88	2.13	0.43
27	US-501	60.42	60.67	0.42
28	41-654	2.13	2.38	0.42
29	15-622	1.00	1.25	0.40
30	41-654	0.13	0.38	0.40
31	US-60	142.32	142.57	0.40
32	SR-151	27.25	27.50	0.39
33	SR-24	49.64	49.89	0.39
34	41-654	0.31	0.56	0.37
35	SR-151	27.13	27.38	0.36
36	71-729	3.69	3.94	0.33
37	US-60	142.26	142.51	0.33
38	SR-151	27.31	27.56	0.29
39	C3US-29	2.25	2.50	0.29
40	41-654	2.06	2.31	0.26
41	71-750	1.94	2.19	0.25
42	US-15	82.12	82.37	0.25
43	C2US-29	1.12	1.37	0.21
44	15-682	18.25	18.50	0.18
45	15-622	0.94	1.19	0.17
46	C3US-29	2.18	2.43	0.17
47	US-501	60.35	60.60	0.13
48	US-15	83.18	83.43	0.12
49	US-15	83.12	83.37	0.12
50	C3US-29	2.06	2.31	0.10

Table B-4. Richmond District (No. 4) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	US-60	194.04	194.29	3.16
2	US-60	194.11	194.36	3.16
3	US-60	194.17	194.42	2.69
4	US-60	193.98	194.23	2.50
5	SR-33	7.28	7.53	2.48
6	SR-33	7.34	7.59	2.19
7	US-60	194.23	194.48	2.03
8	US-60	198.25	198.50	2.03
9	US-60	198.31	198.56	2.01
10	US-60	194.92	195.17	2.00
11	SR-33	7.40	7.65	1.97
12	US-60	197.88	198.13	1.91
13	US-60	194.86	195.11	1.86
14	US-60	198.19	198.44	1.86
15	US-60	197.75	198.00	1.79
16	US-60	194.67	194.92	1.74
17	US-60	194.73	194.98	1.74
18	SR-33	7.47	7.72	1.73
19	US-60	194.98	195.23	1.72
20	US-60	194.79	195.04	1.72
21	US-60	197.94	198.19	1.70
22	US-60	194.61	194.86	1.68
23	SR-271	0.30	0.55	1.66
24	SR-271	0.36	0.61	1.66
25	SR-271	0.43	0.68	1.66
26	US-60	197.81	198.06	1.59
27	US-60	194.54	194.79	1.58
28	SR-33	7.22	7.47	1.58
29	US-60	198.13	198.38	1.49
30	US-60	198.38	198.66	1.47
31	US-60	198.06	198.31	1.45
32	SR-271	0.49	0.74	1.40
33	US-60	198.00	198.25	1.40
34	US-60	195.36	195.61	1.34
35	US-60	195.04	195.29	1.21
36	SR-157	6.72	6.97	1.20
37	US-60	194.48	194.73	1.19
38	SR-33	7.15	7.40	1.19
39	US-60	194.42	194.67	1.14
40	20-645	0.38	0.65	1.10
41	US-60	194.36	194.61	1.07
42	SR-271	0.55	0.80	1.01
43	20-645	0.31	0.56	1.00
44	SR-157	3.36	3.61	0.87
45	20-645	0.25	0.50	0.84
46	20-638	6.15	6.40	0.83
47	42-627	3.84	4.09	0.43
48	42-637	0.38	0.63	0.16
49	20-770	0.31	0.56	0.14
50	42-637	0.31	0.56	0.05

Table B-5. Hampton Roads District (No. 5) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	SR-199	10.58	10.83	1.55
2	SR-199	10.64	10.90	1.59
3	SR-199	10.52	10.77	1.45
4	US-258	29.75	30.00	0.10
5	SR-143	34.02	34.08	0.29
6	SR-199	10.46	10.71	0.96
7	US-58	489.63	489.88	0.86
8	US-58	489.70	489.95	0.86
9	US-58	489.76	490.01	0.86
10	US-58	489.82	490.10	0.96
11	SR-175	0.00	0.25	0.83
12	SR-175	0.06	0.31	0.83
13	SR-175	0.13	0.38	0.83
14	SR-175	0.19	0.44	0.83
15	SR-175	0.25	0.56	1.02
16	99-641	0.63	0.88	0.14
17	99-641	0.56	0.81	0.14
18	46-669	0.00	0.24	0.68
19	99-641	0.69	0.94	0.12
20	US-58	489.57	489.82	0.79
21	99-641	0.50	0.75	0.08
22	99-614	0.38	0.63	0.12
23	47-658	0.00	0.30	0.66
24	SR-171	4.76	5.01	0.33
25	99-646	0.00	0.25	0.48
26	US-58	489.51	489.76	0.73
27	US-60	245.39	245.64	0.56
28	US-258	29.82	30.07	0.13
29	C1US-258	0.50	0.75	0.45
30	99-641	0.75	1.00	0.05
31	46-665	3.25	3.50	0.45
32	US-58	489.45	489.70	0.66
33	46-665	3.31	3.56	0.43
34	SR-171	4.82	5.07	0.30
35	US-60	245.45	245.70	0.46
36	US-58	489.38	489.63	0.60
37	US-58	489.07	489.32	0.60
38	US-58	489.13	489.38	0.60
39	US-58	489.20	489.45	0.60
40	US-58	489.26	489.51	0.60
41	US-58	489.32	489.57	0.60
42	C1US-258	1.88	2.13	0.58
43	C1US-258	1.56	1.81	0.56
44	SR-5	45.60	45.85	0.24
45	US-60	245.32	245.57	0.45
46	US-60	245.51	245.76	0.46
47	C1US-258	0.44	0.69	0.36
48	46-665	3.38	3.63	0.40
49	C1US-258	1.94	2.21	0.58
50	SR-35	15.57	15.82	0.10

Table B-6. Fredericksburg District (No. 6) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	88-639	8.50	8.75	5.50
2	88-639	8.56	8.81	3.50
3	89-610	10.60	10.85	2.40
4	88-639	8.63	8.88	1.51
5	89-610	10.66	10.91	1.33
6	88-627	5.49	5.74	1.12
7	US-17	172.53	172.78	1.07
8	88-627	5.43	5.68	1.02
9	88-639	8.69	8.94	0.89
10	88-627	5.56	5.81	0.82
11	SR-206	9.24	9.49	0.82
12	88-639	8.75	9.00	0.81
13	89-610	10.73	10.98	0.80
14	US-17	172.47	172.72	0.76
15	88-627	5.37	5.62	0.72
16	SR-206	9.31	9.56	0.68
17	C2US-17	3.66	3.91	0.66
18	88-639	8.81	9.06	0.58
19	89-641	0.88	1.13	0.55
20	C2US-17	3.60	3.85	0.53
21	88-628	3.79	4.04	0.53
22	C2US-17	3.73	3.98	0.50
23	88-710	0.00	0.25	0.48
24	88-639	8.88	9.13	0.47
25	89-630	4.82	5.07	0.46
26	88-627	5.31	5.56	0.42
27	89-648	5.46	5.71	0.42
28	89-648	5.52	5.80	0.41
29	89-630	4.89	5.14	0.40
30	88-636	1.75	2.00	0.37
31	88-610	7.31	7.56	0.36
32	88-627	4.74	4.99	0.35
33	89-610	9.23	9.40	0.35
34	88-627	4.81	5.06	0.32
35	88-627	4.68	4.93	0.30
36	89-641	0.00	0.25	0.28
37	89-610	8.58	8.83	0.26
38	89-610	8.52	8.77	0.26
39	89-610	8.64	8.89	0.26
40	C2US-17	3.54	3.79	0.26
41	C1US-1	0.07	0.32	0.23
42	88-636	1.31	1.56	0.23
43	88-620	10.61	10.86	0.16
44	89-1482	0.63	0.88	0.15
45	89-1482	0.69	0.94	0.15
46	C1US-1	1.26	1.52	0.15
47	89-610	8.45	8.70	0.13
48	89-1482	0.75	1.00	0.13
49	89-610	8.70	8.97	0.12
50	89-1482	0.56	0.81	0.10

Table B-7. Culpeper District (No. 7) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	SR-22	24.66	24.91	1.07
2	SR-22	24.60	24.85	1.00
3	02-631	11.40	11.65	0.94
4	02-631	11.46	11.71	0.94
5	02-631	11.53	11.78	0.94
6	02-631	11.59	11.84	0.94
7	02-631	11.65	11.90	0.94
8	02-631	11.71	11.96	0.94
9	02-631	11.78	12.03	0.94
10	US-250	91.71	91.96	0.89
11	02-631	11.84	12.09	0.88
12	SR-20	44.00	44.25	0.85
13	US-250	91.77	92.02	0.85
14	SR-20	43.94	44.19	0.80
15	SR-22	24.73	24.98	0.78
16	SR-20	43.87	44.12	0.74
17	SR-20	44.06	44.31	0.71
18	C1US-250	0.55	0.85	0.69
19	02-631	14.35	14.60	0.68
20	SR-20	43.81	44.06	0.68
21	02-631	11.90	12.15	0.65
22	02-631	14.41	14.66	0.63
23	US-250	91.65	91.90	0.62
24	02-742	1.13	1.38	0.61
25	SR-20	43.75	44.00	0.61
26	US-15	111.80	112.05	0.59
27	SR-3	9.90	10.19	0.59
28	02-742	1.19	1.44	0.54
29	SR-20	43.62	43.87	0.54
30	02-855	0.00	0.25	0.53
31	SR-20	44.12	44.37	0.52
32	US-15	144.44	144.69	0.51
33	SR-20	43.56	43.81	0.51
34	02-866	0.19	0.44	0.49
35	US-15	111.73	111.98	0.47
36	US-15	111.86	112.11	0.46
37	US-250	88.68	88.93	0.46
38	US-15	144.38	144.63	0.46
39	US-15	144.26	144.51	0.44
40	02-631	11.96	12.21	0.42
41	SR-28	2.62	2.87	0.41
42	SR-53	11.94	12.19	0.40
43	US-250	88.62	88.87	0.33
44	23-729	6.06	6.31	0.31
45	23-729	5.99	6.24	0.27
46	SR-20	76.84	77.09	0.23
47	US-33	86.87	87.16	0.12
48	US-33	86.81	87.06	0.12
49	02-652	0.25	0.50	0.11
50	30-858	0.00	0.10	0.05

Table B-8. Staunton District (No. 8) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	US-11	325.70	325.95	1.61
2	US-11	325.64	325.89	1.50
3	US-11	325.77	326.02	1.37
4	US-11	325.58	325.83	1.09
5	US-11	325.83	326.08	0.95
6	US-11	202.94	203.22	0.89
7	34-622	12.40	12.65	0.83
8	34-622	12.46	12.71	0.82
9	US-11	202.88	203.13	0.79
10	US-11	325.52	325.77	0.74
11	US-11	202.82	203.07	0.74
12	US-11	202.76	203.01	0.69
13	US-11	300.10	300.35	0.65
14	US-11	202.69	202.94	0.65
15	34-622	12.53	12.78	0.61
16	US-11	202.63	202.88	0.61
17	US-11	300.16	300.41	0.61
18	34-622	12.34	12.59	0.53
19	SR-252	26.06	26.31	0.51
20	US-11	325.89	326.14	0.50
21	SR-277	1.13	1.38	0.50
22	US-11	300.22	300.47	0.50
23	SR-252	26.00	26.25	0.50
24	SR-42	271.03	271.29	0.46
25	SR-130	0.00	0.25	0.46
26	SR-252	25.94	26.19	0.46
27	SR-130	0.06	0.31	0.45
28	SR-252	26.13	26.38	0.45
29	US-11	325.45	325.70	0.41
30	SR-42	270.97	271.22	0.40
31	SR-55	24.12	24.37	0.40
32	SR-252	26.19	26.44	0.39
33	SR-252	26.25	26.50	0.36
34	SR-285	0.09	0.34	0.35
35	SR-55	23.50	23.75	0.34
36	SR-55	23.56	23.81	0.31
37	07-608	27.85	28.10	0.30
38	07-608	27.91	28.16	0.29
39	SR-285	0.15	0.40	0.28
40	07-608	15.38	15.63	0.27
41	07-608	15.44	15.69	0.27
42	07-608	13.69	13.94	0.26
43	07-608	15.31	15.56	0.22
44	SR-42	270.91	271.16	0.22
45	US-340	121.98	122.01	0.12
46	07-608	15.25	15.50	0.10
47	34-1070	0.38	0.63	0.07
48	34-1070	0.31	0.56	0.07
49	34-1070	0.25	0.50	0.07
50	34-1070	0.44	0.69	0.03

Table B-9. Northern Virginia District (No. 9) Prioritization by EB Method

Rank	Route	STARTMP	ENDMP	Potential for Safety Improvement (PSI) Crashes/yr
1	29-617	4.80	5.05	5.40
2	29-657	7.97	8.22	5.28
3	29-657	8.03	8.28	4.59
4	29-657	7.90	8.15	4.17
5	29-617	4.87	5.12	4.09
6	29-617	4.93	5.18	3.88
7	29-657	8.09	8.34	3.75
8	29-617	4.99	5.24	3.71
9	29-617	5.05	5.35	3.37
10	29-617	4.74	4.99	3.07
11	29-657	7.84	8.09	2.46
12	76-2000	2.44	2.69	2.34
13	29-638	3.14	3.40	2.33
14	29-638	3.01	3.26	2.19
15	29-638	3.07	3.32	2.19
16	29-638	2.95	3.20	2.07
17	76-2000	2.88	3.13	2.07
18	76-2000	2.94	3.19	2.07
19	76-2000	3.00	3.25	2.07
20	76-2000	3.07	3.32	2.07
23	29-684	0.74	0.99	2.06
21	29-643	12.04	12.31	1.97
22	29-657	8.15	8.43	1.96
24	29-684	0.68	0.93	1.81
25	29-650	5.98	6.23	1.80
26	76-2000	2.82	3.07	1.74
27	76-640	6.20	6.45	1.70
28	76-640	6.27	6.52	1.68
29	SR-309	3.35	3.60	1.68
30	29-645	3.19	3.44	1.68
31	29-645	3.25	3.50	1.68
32	29-645	3.32	3.57	1.68
33	29-645	3.38	3.63	1.68
34	29-684	0.81	1.06	1.67
35	SR-28	19.46	19.71	1.66
36	76-2000	3.13	3.38	1.66
37	29-633	0.00	0.25	1.62
38	29-650	5.92	6.17	1.59
39	29-643	11.98	12.23	1.55
40	SR-28	19.53	19.78	1.54
41	SR-309	3.29	3.54	1.53
42	29-645	3.44	3.69	1.52
43	29-657	7.78	8.03	1.52
44	76-2000	2.50	2.75	1.48
45	29-638	2.89	3.14	1.48
46	SR-193	8.44	8.69	1.47
47	SR-287	0.50	0.75	1.45
48	SR-309	3.23	3.48	1.40
49	SR-287	0.44	0.69	1.40
50	29-633	2.25	2.55	1.37