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SAFETY PERFORMANCE FUNCTIONS FOR INTERSECTIONS ON HIGHWAYS MAINTAINED BY THE VIRGINIA DEPARTMENT OF TRANSPORTATION

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In recent years, significant effort and money have been invested through research and implemented safety projects to enhance highway safety in Virginia. However, there is still substantial room for improvement in both crash frequency and severity. As there are limits in the available funds for safety improvements, it is crucial that allocated resources for safety improvement be spent at highway locations that will result in the maximum safety benefits. In addition, intersection crashes play a significant role in the safety conditions in Virginia. For example, crashes at intersections in Virginia for the period 2003 through 2007 account for 43.8% of all crashes and 26% of fatal crashes. Therefore, identifying intersections for safety improvements that will give the highest potential for crash reduction when appropriate safety countermeasures are implemented will have a significant impact on the overall safety performance of roads in Virginia.

The Federal Highway Administration (FHWA) has developed a procedure for identifying highway locations that have the highest potential for crash reduction (ITT Corporation, 2008). A critical component of this method is the use of safety performance functions (SPFs) to determine the potential for crash reductions at a location. An SPF is a mathematical relationship (model) between frequency of crashes by severity and the most significant causal factors on a specific highway. Although the *SafetyAnalyst User's Manual* presents several SPFs for intersections, these were developed using data from Minnesota. FHWA also suggested that if feasible, each state should develop its own SPFs based on crash and traffic volume data from the state, as the SPFs that are based on Minnesota data may not adequately represent the crash characteristics in all states. SPFs for intersections in Virginia were developed using the annual average daily traffic as the most significant causal factor, emulating the SPFs currently suggested by SafetyAnalyst. The SPFs were developed for both total crashes and combined fatal plus injury crashes through generalized linear modeling using a negative binomial distribution. Models were also developed for urban and rural intersections separately, and in order to account for the different topographies in Virginia, SPFs were also developed for three regions: Northern, Western, and Eastern.

This report covers Phases I and II of the study, which includes urban and rural intersections maintained by VDOT. Statistical comparisons of the models based on Minnesota data with those based on the Virginia data showed that the specific models developed for Virginia fit the Virginia crash data better. The report recommends that VDOT's Traffic Engineering Division use the SPFs developed for Virginia and the specific regional SPFs suggested in this report to prioritize the locations in need of safety improvement.

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DISCLAIMER

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ABSTRACT

In recent years, significant effort and money have been invested through research and implemented safety projects to enhance highway safety in Virginia. However, there is still substantial room for improvement in both crash frequency and severity. As there are limits in the available funds for safety improvements, it is crucial that allocated resources for safety improvement be spent at highway locations that will result in the maximum safety benefits. In addition, intersection crashes play a significant role in the safety conditions in Virginia. For example, crashes at intersections in Virginia for the period 2003 through 2007 account for 43.8% of all crashes and 26% of fatal crashes. Therefore, identifying intersections for safety improvements that will give the highest potential for crash reduction when appropriate safety countermeasures are implemented will have a significant impact on the overall safety performance of roads in Virginia.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) is continually identifying ways to enhance the achievement of Virginia's broad vision statement to make Virginia's surface transportation system the safest in the nation by 2025 (Virginia Surface Transportation Safety Executive Committee, 2006). Reductions in crash occurrence and severity at intersections will significantly contribute to the overall safety improvements in Virginia, as intersection crashes form a large proportion of crashes that occur on Virginia's surface transportation system. For example, Table 1 shows that for 2003 through 2007, intersection crashes on VDOT-maintained roads accounted for about 44% of all crashes, and Table 2 shows that about 26% of fatal crashes occurred at intersections.

In addition, because of limited funds, it is crucial that allocated resources for safety improvement be spent at highway locations that will result in the maximum safety benefits. The Federal Highway Administration (FHWA) has developed a prioritization methodology for safety improvements using the empirical Bayes (EB) method. This method prioritizes sites for safety improvement to obtain the greatest safety benefits (ITT Corporation, 2008). This procedure requires the use of safety performance functions (SPFs). An SPF relates the frequency of crashes by severity with the most significant causal factors on a specific type of road. For example, Figure 1 shows a schematic graph of an SPF for a highway segment to demonstrate how it is used in site prioritization.

Table 1: Total and Intersection Crashes For 2003 Through 2007

Year	Total Crashes	Intersection Crashes	Proportion (%)
2003	94,817	41,116	43.4
2004	95,063	42,042	44.2
2005	96,066	42,064	43.8
2006	93,732	41,714	44.5
2007	89,394	38,695	43.3
TOTAL	469,072	205,631	43.8

Table 2: Total Fatal and Intersection Fatal Crashes for 2003 Through 2007

Year	Total Fatal Crashes	Intersection Fatal Crashes	Proportion (%)
2003	726	216	29.8
2004	723	188	26.0
2005	752	188	25.0
2006	722	193	26.7
2007	778	184	23.7
TOTAL	3,701	969	26.2

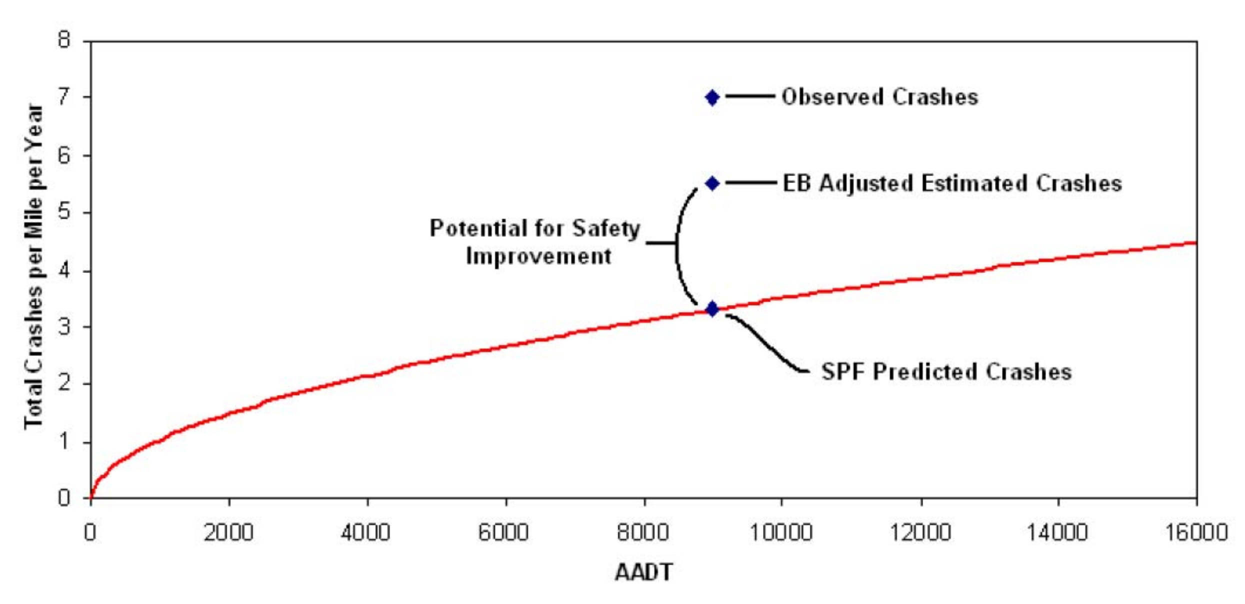

Figure 1: Example of a Safety Performance Function (SPF)

SPFs are developed for different roadway segments and intersection configurations. Currently, the SPFs suggested by FHWA use only annual average daily traffic (AADT) as the most significant causal factor. For example, an intersection SPF gives the predicted number of crashes per year, for given AADTs on the major and minor approaches. SPFs aid the transportation planner to identify better where to expend limited staff resources on detailed assessments to determine feasible and effective treatments. AADT-driven SPFs are practical for network screening. Adding more independent variables beyond AADT may be too labor intensive. The corresponding EB-adjusted long-term number of crashes can be computed from the actual observed crashes and the SPF-predicted number of crashes for the given AADT. As it can be seen in Figure 1, the difference between the EB-adjusted long-term number of crashes and the SPF-predicted number of crashes gives the potential for safety improvement (PSI). The PSI can be better described as the potential for intersection sites to be upgraded or repaired by reducing crashes and improving safety if appropriate countermeasures are applied to these sites. This can be used to develop a priority list of the specific sites or intersections where detailed assessments to determine feasible and effective treatment can be undertaken. Sites that have a greater PSI are given a higher prioritization when all selected sites are ranked in order to determine which sites should receive prompt attention.

SafetyAnalyst provides a set of state-of-the art software tools for use in the decision-making process to identify safety needs and develop a program for site-specific safety improvement projects. SafetyAnalyst also plays an important role because it helps make sure that highway agencies receive the greatest possible safety benefit from every dollar spent toward safety modifications (FHWA, 2010). FHWA-suggested SPFs for intersections are, however, based on data from Minnesota, and it has been recommended that individual states develop SPFs based on their own crash and AADT data (Harwood et al., 2004). The development of SPFs for Virginia is of great importance when safety improvement is being considered. Because of the important role SPFs play in the software tools in SafetyAnalyst, it is essential at least to test how well the FHWA-suggested SPFs fit the Virginia data and if necessary to develop specific SPFs for Virginia.

PURPOSE AND SCOPE

The purpose of this study was to investigate the extent to which the FHWA-suggested intersection SPFs, which were based on Minnesota data, were transferable to Virginia and, if necessary, to develop Virginia-specific SPFs using crash and corresponding AADTs for intersection sites in Virginia. The SPFs for this study include those for total crashes and combined fatal and injury (FI) crashes with different configurations, such as four-leg and three-leg intersections, signalized intersections and unsignalized intersections or urban and rural locations.

The scope was limited to intersection types on VDOT-maintained roads for which appropriate and adequate data were available. This report gives the results obtained for urban and rural intersections. The objectives were as follows:

1. Evaluate the transferability of the FHWA-suggested SPFs to Virginia.
2. If necessary, develop SPFs for different intersection types that are suitable for use in Virginia.
3. Identify some of the intersections that have a higher than expected number of crashes.

Crashes related to two-lane roads were investigated in a separate study (Garber et al., 2010). It is anticipated that the results obtained from both studies will produce a set of SPFs that can be applied to Virginia and be used to prioritize those two-lane segments and intersections that are in need of safety improvements, thereby improving the transportation planning process.

METHODS

Ten tasks were performed to achieve the study objectives:

1. Conduct a literature review.
2. Select study sites.
3. Extract crash data.
4. Extract AADT data.
5. Evaluate the transferability to Virginia of the suggested Minnesota SPFs.
6. Develop specific SPFs for Virginia.
7. Evaluate the Virginia SPFs developed.
8. Determine the appropriate number of SPFs for Virginia through a pruning process.
9. Prioritize sites based on potential for crash reduction.
10. Evaluate benefits and implementation prospects.

Literature Review

Recent publications related to the development and evaluation of SPFs for different highway systems were identified and reviewed so as to identify information of relevance to this study. Sources used were the Transportation Research Information System (TRIS), the VDOT Research Library, and the University of Virginia libraries.

Selection of Study Sites

The research team, in consultation with staff from VDOT's Traffic Engineering Division (TED), initially selected 21,112 intersections under the jurisdiction of VDOT for the study. These included all intersections for which the location was properly identified by an intersection node and for which geometric characteristics remained the same throughout the study period of 2003 through 2007. The required geometric, traffic and crash data for each site were then extracted from the relevant databases. The data were obtained primarily from the Highway Traffic Records Information System (HTRIS). HTRIS is a comprehensive Oracle database system, which 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. For this reason, only VDOT-maintained roads were used for analysis. This database system contains multiple subsystems, three of which were used to extract data for this study: roadway inventory (RDI) for intersection configuration and type of control, accident (ACC) for crash counts, and highway performance monitoring system (HPMS) for AADTs. Using the available data, each intersection was classified based on the area type (urban or rural), the traffic control system (signalized, stop control, or yield control), and the configuration (number of approaches). Intersections for which all the data requirements for proper classification were not available were deleted from the list of study sites.

The classification of an intersection as urban or rural was based on VDOT's classification of each approach route. Intersections with all approaches designated as rural were classified as rural and those with all approaches designated as urban were classified as urban. Intersections with urban and rural approaches were removed from the list of study sites to minimize the uncertainty. A data quality analysis was also performed to ascertain that the AADT values for all approaches of each intersection and for each year of the study period were available. Intersections with incomplete data were removed from the study including yield, all-way stop, and intersections with five approaches. This resulted in 18,356 intersections classified as urban or rural as shown in Table 3.

Virginia is divided into five operational regions as shown in Figure 2. After consultation with VDOT and the technical review panel, the different topographical characteristics in Virginia were then used to group the intersections into three regional groups as Northern, Western, and Eastern. The Northern region is composed of intersections in Northern Virginia and surrounding counties, the Western region is considered to have a mountainous terrain, and the Eastern region is considered to have rolling to flat terrain. Table 3 also shows the specific districts and counties in each of the three regions used in this study. This regional classification helped to partially account for different characteristics that are encountered throughout the state.

Table 3: Urban and Rural Classification

Operational Region	Districts	Urban	Rural	Total
Northern (No. 1)*	District 9 (NOVA) + Culpeper (023), Fauquier County (030), King George County (048), Madison County (056), Orange County (068), Rappahannock County (078), Spotsylvania (088), Stafford County (089)	4620	596	5216
Western (No. 10)*	District 1 (Bristol), District 2 (Salem), District 3 (Lynchburg), District 8 (Staunton) + Albemarle County (002), Fluvanna County (032), Greene County (039), Louisa County (054)	1197	6706	7903
Eastern (No. 100)*	District 4 (Richmond) and District 5 (Hampton Roads) + Caroline County (016), Essex County (028), Gloucester County (036), King & Queen County (049), King William (050), Lancaster County (051), Mathews County (057), Middlesex County (059), Northumberland County (066), Richmond County (079), Westmoreland County (096)	2193	3044	5237
Total		8010	10346	18356
Proportion (%)		43.64	56.36	100

*Alternative method of identifying regions for easy application of the SAS code: No. 1 = Northern region; No. 10 = Western region; No. 100 = Eastern region.

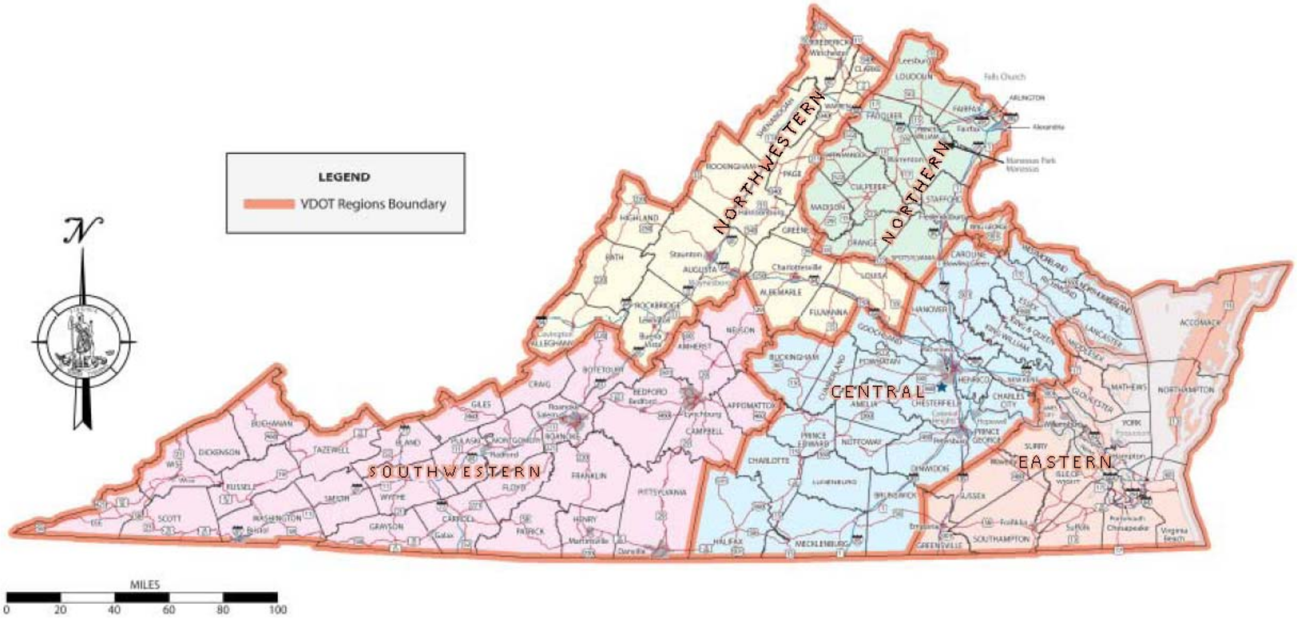

Figure 2: Virginia Operational Regions (Cogburn, 2007)

The study considered urban and rural intersections, with urban consisting of 8,010 intersections and rural consisting of 10,346 intersections as shown in Table 4.

The intersections were also divided by their configuration (number of approaches) and the type of traffic control (signalized or minor stop control). The number of urban intersection sites for each category is shown in Table 5 and that for rural intersections in Table 6. The total number of rural four-leg signalized and rural three-leg signalized sites is much lower than that for the urban signalized intersections. However, this is expected as a much lower percentage of rural intersections are signalized. In addition, all-way stop intersections were excluded because of the low number at the time of the study.

Table 4: Proportion of Urban and Rural Sites by Region

Operational Region	Urban	Proportion (%)	Rural	Proportion (%)
Northern	4620	57.68	596	5.760
Western	1197	14.94	6706	64.817
Eastern	2193	27.38	3044	29.423
TOTAL	8010	100	10346	100

Table 5: Distribution of Urban Sites by Geometric Configuration

Operational Region	Urban 4-leg Signalized	Urban 4-leg 2-Way Stop	Urban 3-leg Signalized	Urban 3-leg Minor Stop	Total
Northern	371	766	497	2986	4620
Western	53	153	137	854	1197
Eastern	144	320	202	1527	2193
TOTAL	568	1239	836	5367	8010
Proportion (%)	7.09	15.47	10.44	67.00	100

Table 6: Distribution of Rural Sites by Geometric Configuration

Operational Region	Rural 4-leg Signalized	Rural 4-leg 2-Way Stop	Rural 3-leg Signalized	Rural 3-leg Minor Stop	Total
Northern	19	67	13	497	596
Western	90	894	117	5605	6706
Eastern	73	609	53	2309	3044
TOTAL	182	1570	183	8411	10346
Proportion (%)	1.76	15.17	1.77	81.30	100

Crash and Operational Data Collection

As previously discussed, HTRIS serves as a centralized warehouse of traffic and roadway data for Virginia and is composed of various subsystems that carry distinct data. RDI, ACC, and HPMS were the three subsystems used to extract the necessary data for the study.

VDOT's TED staff extracted the crash data by using the ACC database for the years 2003 through 2007. The ACC database is composed of data derived from the crash report forms (DMV FR300) that are filled out by police officers and include data such as driver's actions, driver characteristics, environmental conditions, collision type, and crash severity, among other factors. The database developed for this study included total, fatal, injury, and property damage only (PDO) (property damage greater than $1,000) crashes that occurred within a distance of 250 feet or 0.047 mile of the intersection, which matches the procedure used to develop the suggested SPFs in SafetyAnalyst. The RDI database was used to identify the intersection ID or node number for the urban and rural intersection sites that had the same geometric conditions throughout the 5 years selected for the study.

A Structured Query Language (SQL) program was developed for retrieving and formatting the required data for the analysis. This query specified the intersection node, configuration, approach volumes, urban/rural classification, crashes, and traffic control device for each year of the study period. The Statistical Analysis Software SAS (9.1.3) was then used to format the data in a way suitable for the analysis (SAS Institute Inc., 2009).

Annual Average Daily Traffic Selection

The major and minor AADTs were used as the independent variables in developing the SPFs for intersections in Virginia, in accordance with the SPFs developed for SafetyAnalyst (Harwood et al., 2004). It was therefore necessary to identify the major and minor approaches at each intersection. In determining the major and minor AADTs, it was recommended by VDOT that for four-leg approaches, the major entering volume should be the sum of the two highest approach volumes and the minor entering volume the sum of the two lowest approach volumes. For three-leg approaches, the major entering volume was the sum of the two highest approach volumes. The highway performance monitoring system database was used to obtain the AADTs for the selected study sites.

Evaluation of Recommended Minnesota SPFs

Once all of the necessary data were obtained for each of the study sites, the SafetyAnalyst-recommended SPFs, which are based on data for intersections in Minnesota, were tested to determine how well they fit the Virginia data. Both graphical and statistical methods were used to conduct these tests. The graphical method consisted of a visual inspection of the spread of the Virginia data for a specific configuration of intersection and the actual crashes of a given severity, plotted with the resultant curve from using the same Virginia database and the corresponding recommended Minnesota SPF. The statistical test consisted of computing the Freeman-Tukey $R_{FT}{}^{2}$ coefficients for the recommended SPFs using the appropriate Virginia data. The R_{FT}^{2} coefficient was used as this was the statistical parameter used to represent the goodness of fit (ITT Corporation, 2008) in developing the SafetyAnalyst-recommended SPFs. Equations 1, 2, and 3 show how the data were transformed to compute the R_{FT}^{2} (Fridstrøm et al., 1995).

$$f_i = (y_i)^{0.5} + (y_i +1)^{0.5} \qquad \text{(Eq. 1)}$$

$$\hat{e}_i = f_i - (4 \times \hat{y}_i + 1)^{0.5} \qquad \text{(Eq. 2)}$$

$$R_{FT}^{2} = 1 - \textstyle\sum_i \hat{e}_i^{2} / \sum_i (f_i - f_m)^{2} \qquad \text{(Eq. 3)}$$

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 (f_i) across all sites of the same configuration and urban/rural classification
R_{FT}^{2} = Freeman-Tukey R^2.

Developing Virginia-Specific SPFs

The format of the specific SPFs developed for Virginia is the same as that in the SafetyAnalyst manual, and given as:

$$\hat{k} = e^{\alpha}\, x\, MajAADT^{\beta_1}\ x\ MinAADT^{\beta_2} \qquad \text{(Eq. 4)}$$

where

$\hat{k}$ = predicted crash frequency per intersection per year
MajAADT = AADT on the major road (veh/day)
MinAADT = AADT on the minor road (veh/day)
α = intercept

β_1 = coefficient of major AADT
β_2 = coefficient of minor AADT.

In developing the SPFs, a negative binomial (NB) distribution for the crash data was used, as preliminary analysis showed that the data fit the NB distribution. The form of the data used to develop the SPFs can be either the panel or cross-sectional (collapsed) format. According to Kweon and Lim (2010), the panel format uses original panel data, which consist of assembling several years of data over the same intersection, and the cross-sectional models use pseudo–cross-sectional data, which are data converted or rearranged from the panel set. The difference between the two types of models obtained is that the model based on the panel data form takes advantage of the characteristics of the panel data by positioning a predefined correlation structure on reciprocated measures over years at the same time whereas the model based on the cross-sectional form uses the data created by collapsing the multi-year panel data into apparently a single-year panel data. The crash data were divided into the estimation and validation portions. Seventy percent was selected randomly and used as the estimation data to develop the SPFs, and the remaining 30% was used as the evaluation data.

An estimation of acceptable values was made for the regression coefficients and the dispersion parameter when developing the SPFs for the EB method in SafetyAnalyst. The regression coefficients are critical for the comparison of different SPFs. The dispersion parameter (d) is important when using the EB method in SafetyAnalyst because it plays an integral function in computing the EB weight that influences the estimate of the EB long-term predicted crashes. When determining the dispersion parameter from SAS for the urban four-leg signalized intersections, the values obtained were d = 0.2223 for the panel data and d = 0.2216 for the collapsed data, but when determining the values for the urban four-leg two-way stop intersections the values calculated were d = 0.4284 for panel data and d = 0.2518 for collapsed data. In the urban four-leg two-way stop intersections, a significant difference in the d values was observed, which led to the choice of panel data for the modeling as they would be more reliable than the collapsed data. By looking at the obtained values, it can be appreciated that the collapsed model underestimates the dispersion, which will eventually cause the EB value to inflate, therefore leading to a biased report for the collapsed model.

Generalized linear modeling (GLM) was used to create a correlation between the intersection crashes for the 5 years chosen for analysis and the major and minor approach volumes. For the statistical modeling, SAS was employed (SAS Institute Inc., 2009). This software includes the GENMOD procedure, and the equation used is the same as given in Equation 5. The GENMOD procedure gives an output of generalized estimating equations (GEE) parameter estimates, which are the ones used to develop the Virginia SPFs.

$$k_{it} = \exp(\alpha + \beta_1 MajAADT + \beta_2 MajAADT) + \varepsilon_{it} \qquad \text{(Eq. 5)}$$

where

i = intersection index (i = 1,…, N)
t = severity index (*t* = *TOT* [total crashes], *FI* [fatal + injury crashes], *PDO* [property damage only])

α = intercept
β_1 = coefficient of major AADT
β_2 = coefficient of minor AADT
k_{it} = dependent variable at intersection i and severity t (crashes/yr)
ν_{it} = random error, exp (ν_{it}), Gamma (θ, θ)
ε_{it} = random (residual) error in GEE.

The random errors presented in this equation have the function of not letting the β values or coefficients become biased.

Evaluation of Virginia-Specific SPFs

Several statistical parameters were used to assess how well the Virginia SPFs fit the data. The parameters used, and suggested by Washington et al. (2005), were the mean prediction bias (MPB), the mean absolute deviation (MAD), the mean square error (MSE), the mean squared prediction error (MSPE), the Pearson's product moment correlation coefficients between observed and predicted crash frequencies (used for both validation and estimation data) dispersion parameters, and the Freeman Tukey $R_{FT}{}^2$ coefficients, computed from Equation 3. To test the fit of the SPFs, the 70% estimation data set was used to calculate the MSE, the Pearson's product moment correlation coefficients, the R^2 and the R^2_{FT}. To test the transferability of the SPFs, the 30% validation data set was used to compute the MPB, MAD, and the MSPE. The expressions used to determine these coefficients are given in Equations 6 through 10.

$$\mathrm{MPB} = \frac{\sum_{i=1}^{n_2}\left(\hat{Y}_i - Y_i\right)}{n_2} \qquad \text{(Eq. 6)}$$

$$\mathrm{MAD} = \frac{\sum_{i=1}^{n_2}\left|\hat{Y}_i - Y_i\right|}{n_2} \qquad \text{(Eq. 7)}$$

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n_2}\left(Y_i - \hat{Y}_i\right)^2}{n_1 - p} \qquad \text{(Eq. 8)}$$

$$\mathrm{MSPE} = \frac{\sum_{i=1}^{n_2}\left(Y_i - \hat{Y}_i\right)^2}{n_2} \qquad \text{(Eq. 9)}$$

where

p = degrees of freedom
i = intersection index
Y_i = observed crash frequency at intersection i
$\hat{Y}_i$ = predicted crash frequency at intersection i

n_2 = validation data sample size 30%
n_1 = estimation data sample size 70%.

$$r = \frac{\sum\left(Y_{i1} - \overline{Y}_1\right)\left(Y_{i2} - \overline{Y}_2\right)}{\left[\sum\left(Y_{i1} - \overline{Y}_1\right)^2 x \sum\left(Y_{i2} - \overline{Y}_2\right)^2\right]^{1/2}} \qquad \text{(Eq. 10)}$$

where

$\bar{Y}_1$ = average of observed crashes per intersections

$\bar{Y}_2$ = average of predicted crashes per intersections
Y_{i1} = observed values at intersection i
Y_{i2} = predicted values at intersection i.

It should be noted that when values obtained from the MPB, MAD, MSE, and MSPE formulas are close to 0, it indicates a good fit or desirable SPF and when values for the R_{FT}^2 and R^2 formulas are close to 1, it indicates a suitable fit.

The dispersion parameter (d) is used in the variance-mean relationships as shown in Equations 11 and 12:

$$Var\left\{m\right\} = E\left\{m\right\} + d \ x \ E\left\{m\right\}^2 \qquad \text{(Eq. 11)}$$

$$Var\left(Y_i \middle| X_i\right) = E\left(Y_i \middle| X_i\right) + d \ x \ E\left(Y_i \middle| X_i\right) \qquad \text{(Eq. 12)}$$

A weighting factor (W_i) used in the EB procedure is obtained from Equation 13 and used in Equation 14 to obtain the EB-estimated value.

$$W_i = \frac{1}{\left(1 + d \ x \ E\left\langle Y_i \middle| X_i \right\rangle\right)} \qquad \text{(Eq. 13)}$$

$$E_{EB}\left\langle E\left(y_i\right) \middle| y_i \right\rangle = W_i \ x \ E\left\langle Y_i \middle| X_i \right\rangle + \left(1 - W_i\right) x \left(Y_i\right) \qquad \text{(Eq. 14)}$$

where

$0 < W < 1$
$Var(\cdot|\cdot)$ = conditional variance
$E(\cdot|\cdot)$ = conditional mean
$Var\{m\}$ or $Var(Y_i|X_i)$ = estimated variance of mean crash rate
$E\{m\}$ or $E(Y_i|X_i)$ = estimated mean crash rate from SPF
d = estimated NB dispersion parameter (also called overdispersion parameter)

W = weight
X_i = variables such as AADT
Y_i = number of observed crashes per year at intersection i
E_{EB} = EB-adjusted estimated crashes (crashes/yr).

In the variance-mean relationship, if the value obtained for the dispersion parameter d is 0, then the variance is the same as the mean (see Equations 11 and 12), which causes the NB model to collapse to the Poisson model. This parameter has a strong influence on the weight in the EB formula (see Eq. 13); therefore, it has an effect in the EB-estimated value. SAS was helpful in computing this parameter for the different types of intersections analyzed in the study throughout the 5 years.

Pruning Process

Before the site prioritization was performed, pruning was done to avoid over-representation of the SPFs that might not reflect much difference in the study when compared with statewide SPFs. At the completion of the pruning process, only the necessary or minimum effective SPFs were retained. MSPE is typically the parameter used to assess errors associated with a validation data set; for this reason, MSPE was used for pruning. In order to verify whether a specific regional SPF should be retained or not, the validation data set (30% of the data) was used to compute MSPE for both the specific regional SPFs and the corresponding statewide SPFs. If MSPE for the regional SPF was greater than that for the corresponding Virginia statewide SPF or if the difference between these two MSPEs was less than 10%, it was concluded that the regional SPF was not necessary and it was therefore discarded. The following example illustrates the steps for urban four-leg signalized FI crashes in Region 1:

1. The 30% FI crash data were obtained for urban signalized four-leg intersections in Region 1, and the MSPE was determined using the statewide SPF for the FI urban four-leg signalized intersections.

2. The 30% FI crash data for urban signalized four-leg intersections in Region 1 were then used to determine MSPE for the specific Region 1 SPF for FI crashes.

3. Verify if the MSPE value for the specific regional SPF is higher than the statewide MSPE value; if yes, discard the specific regional SPF; if no tentatively retain the specific regional model.

4. The difference between the two MSPEs was determined to determine whether it was less than 10% of the statewide MSPE; if yes, discard the specific regional SPF; if no, retain the specific regional model. This process was repeated for all regional SPFs.

Identification of Intersections with a Higher Than Expected Number of Crashes

In order to identify some of the intersections with a higher than expected number of crashes, a prioritization analysis based on the EB method was conducted. This analysis was carried out to identify the top 25 intersections with a high PSI in the urban areas of the Northern Virginia and Bristol districts. These two districts were selected to identify any effect of the approach AADTs as two-lane roads in the Northern Virginia District carry much higher volumes than those in the Bristol District. The PSI is the difference between the EB-adjusted long-term crashes and the SPF-estimated crashes. The PSI was first determined, and then a priority list was developed, with intersections showing a higher PSI receiving a higher priority. This procedure first required the computation of yearly calibration factors (C_y) that accounted for intrinsic yearly variations that were not accounted for in developing the SPFs. These yearly calibration factors were determined using the steps described here and given in Equations 15 through 18 (ITT Corporation, 2008).

Calculation of Yearly Calibration Factor (C_y)

For subtype *s* and severity *t*, the following steps were performed:

1. Calculate the (unadjusted) predicted number of crashes using the appropriate SPF

$$\tilde{\kappa}_{isty} = e^{\hat{\alpha}_{st}} \times MajAADT_{isy}^{\hat{\beta}_{1st}} \times MinAADT_{isy}^{\hat{\beta}_{2st}}, \; \forall\, i \,\&\, y \qquad \text{(Eq. 15)}$$

2. Sum the predicted numbers over all intersections

$$\tilde{\kappa}_{sty} = \sum_{i=1}^{N_s} \tilde{\kappa}_{isty}, \; \forall\, y \qquad \text{(Eq. 16)}$$

3. Sum the observed numbers of crashes over all intersections

$$K_{sty} = \sum_{i=1}^{N_s} K_{isty}, \; \forall\, y \qquad \text{(Eq. 17)}$$

4. Calculate yearly calibration factor, c_{sty}

$$c_{sty} = \frac{K_{sty}}{\tilde{\kappa}_{sty}}, \; \forall\, y \qquad \text{(Eq. 18)}$$

5. Repeat the steps for all subtypes (*s*) and severities (*t*)

where

i = intersection index ($i = 1, \ldots, N$)

s = subtype index (*s* = urban four-leg signalized intersection, rural three-leg minor stop controlled intersection, etc.)
t = severity index (*t* = *TOT* [total crashes], *FI* [fatal + injury crashes], *PDO* [property damage only])
y = year index (*i* = 1 [base year], 2, …, *Y*)
c_{sty} = yearly calibration factor for crash subtype s, severity t, and year y
MajAADT = AADT on the major road (veh/day)
MinAADT = AADT on the minor road (veh/day)
$\tilde{\kappa}_{isty}$ = (unadjusted) predicted number of crashes at intersection i, for crash subtype s, severity t, and year y
κ_{isty} = (adjusted) predicted number of crashes at intersection i, for crash subtype s, severity t, and year y
$\hat{\alpha}$ = intercept
$\hat{\beta}_1$ = coefficient of major AADT
$\hat{\beta}_2$ = coefficient of minor AADT.

These yearly calibration factors were then used to determine the predicted number of crashes at an intersection based on the SPF for the severity of crashes and type of intersection being considered. The PSI for each intersection was then determined using the steps described in Equations 19 through 22 (ITT Corporation, 2008).

Steps for Calculating PSI for Subtype *s*

1. Calculate the (adjusted) predicted number of crashes

$$\begin{aligned}\kappa_{isty} &= c_{sty} \times \tilde{\kappa}_{isty},\ \forall i, t \,\&\, y \\ &= c_{sty} \times \{e^{\hat{\alpha}_{st}} \times MajAADT_{isy}^{\hat{\beta}_{1st}} \times MinAADT_{isy}^{\hat{\beta}_{2st}}\}\end{aligned} \qquad \text{(Eq. 19)}$$

2. Calculate yearly correction factor, C_{isty}

$$C_{isty} = \frac{\kappa_{isty}}{\kappa_{ist(y=1)}},\ \forall i, t \,\&\, y \qquad \text{(Eq. 20)}$$

3. Calculate EB weight

$$w_{ist} = \frac{1}{1 + d_{st} \times \sum_{y=1}^{Y} \kappa_{isty}},\ \forall i \,\&\, t \qquad \text{(Eq. 21)}$$

4. Calculate the EB-adjusted estimated number of crashes for year 1

$$X_{ist(y=1)} = w_{ist} \times \kappa_{ist(y=1)} + (1 - w_{ist}) \frac{\sum_{y=1}^{Y} K_{isty}}{\sum_{y=1}^{Y} C_{isty}}, \ \forall\, i \,\&\, t \qquad \text{(Eq. 22)}$$

5. Determine the PSI for each intersection

If $X_{istY} > \kappa_{istY}$ include intersection *i* in the list for prioritization using $\mathrm{PSI}_{istY} = X_{istY}$

where

i = intersection index (i = 1,…, N)
s = subtype index (s = urban four-leg signalized intersection, rural three-leg minor stop controlled intersection, etc)
t = severity index (t = *TOT* [total crashes], *FI* [fatal + injury crashes], *PDO* [property damage only])
y = year index (y = 1 [base year], 2, …, Y)
c_y = yearly calibration factor for crash subtype s, severity t and year y
d = dispersion parameter
w = weight
MajAADT = AADT on the major road (veh/day)
MinAADT = AADT on the minor road (veh/day)
PSI = potential for safety improvement
C_{isty} = yearly correction factor
$\tilde{\kappa}_{isty}$ = (unadjusted) predicted number of crashes at intersection i, for crash subtype s, severity t and year y
κ_{isty} = (adjusted) predicted number of crashes at intersection i, for crash subtype s, severity t and year y
X_{isty} = EB-adjusted estimated number of crashes
$\hat{\alpha}$ = intercept
$\hat{\beta}_1$ = coefficient of major AADT
$\hat{\beta}_2$ = coefficient of minor AADT.

The prioritization lists for urban two-lane roads in the Northern Virginia and Bristol districts were then developed based on the PSIs obtained for three prioritization procedures. These alternative prioritization procedures were the average crash rates (ACRs) for the study period (see Equation 23), the critical crash ratio (CCR) (see Eqs. 24 through 27) (Garber and Hoel, 2009), and the EB method. The list was developed with the intersections having the highest PSI listed first, followed by other intersections in descending order. The execution of the EB method prioritization process was achieved through use of the computer codes in SAS. Finally, the effectiveness of using the EB method for prioritizing sites for safety improvement was illustrated by comparing the PSIs from using intersection crash rates, critical crash, and the EB procedures.

Procedure for Crash Rate Method

The ACR for the intersection is given as:

$$ACR = \frac{(TC)(1,000,000)}{(N)(V_T)(365)} \quad \text{(Eq. 23)}$$

where

ACR = the average crash rate for the intersection under consideration (crashes/1,000,000 approach volume)
TC = number of crashes over the study period at the intersection
N = duration of study period (yr)
V_T = average daily total approach volume at the intersection.

Procedure for Critical Rate Method

The critical rate method was accomplished by first computing the traffic base (TB) of the intersection under consideration using Equation 24. The ACR for the intersection under consideration is then computed using its TB as shown in Equation 25. The intersection critical crash rate (ICCR) is then determined using Equation 26. The critical crash ratio (CCR) for the intersection is then computed as the ratio of ICR and the average crash rate (AVR) for all intersections under the same category (intersection type, urban/rural, etc.) as that for the intersection being considered using Equation 27.

TB is given as:

$$TB = \frac{NxVx365}{1,000,000} \quad \text{(Eq. 24)}$$

where

TB = the total approach volume over the study period of N years at the intersection under consideration (veh/1,000,000)
V = average daily approach volume at the intersection under consideration.

ACR is obtained as:

$$ACR = \frac{TC}{TB} \quad \text{(Eq. 25)}$$

where

ACR = ACR at the intersection under consideration over the study period of N years

TB = the total approach volume over the study period of N years at the intersection under consideration (veh/1,000,000).

The critical crash rate (ICCR) for the intersection under consideration is given as:

$$ICCR = AVR + \frac{0.5}{TB} + TF\sqrt{\frac{AVR}{TB}} \qquad \text{(Eq. 26)}$$

where

AVR = ACR for intersections within the state and of the same designation (e.g., rural three-leg with minor stop control) as that for the intersection under consideration
TF = number of standard deviations for the confidence level being used in the analysis (usually 1.96 for 95% confidence level)
TB = the total approach volume over the study period of N years at the intersection under consideration (veh/1,000,000).

The critical crash ratio *(CCR)* for the intersection is then obtained as:

$$CCR = \frac{ACR}{ICCR} \qquad \text{(Eq. 27)}$$

where

ACR = ACR at the intersection under consideration over the study period of N years (see Eq. 2)
ICCR = critical crash rate for the intersection under consideration (see Eq. 26).

Benefits and Implementation Expectations

The expected benefits from developing SPFs and prioritizing intersection sites were illustrated by comparing the PSIs for the prioritized sites when sites were prioritized using the EB method with those obtained when sites were prioritized using crash rates and the critical crash ratio. This analysis was conducted for the combined fatal plus injury crashes SPFs. An estimate of the cost savings, attributable solely to the potential reduction of crashes, was also computed by using crash costs given in an FHWA study (FHWA, 2005).

RESULTS AND DISCUSSION

Literature Review

SafetyAnalyst

The *SafetyAnalyst User's Manual* (ITT Corporation, 2008) has SPFs that are suggested for intersections that are based on Minnesota data. Tables 7 and 8 show the regression coefficients (α, β_1 and β_2) for the SPFs developed for total and combined FI crashes, respectively. The values for the goodness of fit parameter R_{FT}^2 are also given. Although these R_{FT}^2 are all less than 0.45, with a few less than 0.10, it has been suggested that the SPFs used in SafetyAnalyst could provide a realistic estimate of an expected crash frequency as a function of traffic volume and roadway geometry (Pham and Ragland, 2005).

Methodological and Research References

Several studies similar to this study have been conducted in Canada, Colorado, California, Texas, New York, and Minnesota. For example, a study was conducted using data from Colorado, California, and Texas to examine the functional form of the SPFs for urban freeways (Kononov et al., 2008). Five years of crash data were acquired from the respective departments of transportation and the highway safety information system from Colorado. The study revealed that the amount of crashes increased moderately with congestion in segments on urban freeways. This study, however, did not include intersections.

A study by Lyon et al. was conducted in Toronto, Ontario, Canada, to develop SPFs for urban signalized intersections (Lyon et al., 2005). Collision data were gathered for five years and included 1,950 urban intersections. SPFs were developed for different severity levels, impact types, and intersection types, such as four-leg and three-leg intersections. The format used to develop the SPFs is shown in Equation 28. This format is somewhat different from that of Equation 4, suggested in Safety Analyst.

$$\text{Collisions/year} = \alpha\,(F1)^{\beta 1}(F2)^{\beta 2}\exp(\beta_3 X_1 + \beta_4 X_2 + \ldots) \qquad \text{(Eq. 28)}$$

where

α and β_i = the coefficients estimated in the SPF calibration process
F1 and F2 = the entering AADTs on the major and minor roads, respectively
X_i = other independent variables (such as single lane versus multilane approaches, with and without left-turn lanes or right-turn lanes, high and low pedestrian activities or in some cases F1 or F2 or both).

Table 7: SafetyAnalyst's SPFs for Intersections (Total Crashes)

Site subtype Code	**Site subtype Description**	**State**	**Regression coefficients LogIntercept (α)**	**Regression coefficients LogAADTmaj (β_1)**	**Regression coefficients LogAADT min (β_2)**	**Over - dispersion Parameter (k)**	**R_{FT}^2 (%)**	**Number of Sites**	**Max $AADT_{maj}$ (veh/day)**	**Max $AADT_{min}$ (veh/day)**
Rural										
201	Rural 3-leg with minor-road STOP control	MN	-8.78	0.71	0.24	1.07	13.3	1,706	28,500	27,000
202	Rural 3-leg with all-way STOP control	MN	-12.37	1.22	0.27	0.47	41	41	25,300	6,803
203	Rural 3-leg with signal control	MN	-6.57	0.66	0.2	0.33	26	136	36,400	11,500
204	Rural 4-leg with minor-road STOP control	MN	-8.96	0.65	0.47	0.7	29.9	2,114	35,500	26,700
205	Rural 4-leg with all-way STOP control	MN	-12.37	1.22	0.27	0.47	41	41	25,300	6,803
206	Rural 4-leg with signal control	MN	-6.57	0.66	0.2	0.33	26	136	36,400	11,500
Urban										
251	Urban 3-leg with minor-road STOP control	MN	-5.35	0.34	0.28	1.28	5.9	397	68,000	18,900
252	Urban 3-leg with all-way STOP control	MN	-12.37	1.22	0.27	0.47	41	41	25,300	6,803
253	Urban 3-leg with signal control	MN	-9.85	0.97	0.18	0.23	41.4	33	50,000	25,807
254	Urban 4-leg with minor-road STOP control	MN	-3.12	0.27	0.16	0.86	7.6	333	58,870	81,000
255	Urban 4-leg with all-way STOP control	MN	-12.37	1.22	0.27	0.47	41	41	25,300	6,803
256	Urban 4-leg with signal control	MN	-3.47	0.42	0.14	0.32	26.4	418	75,000	81,000

ITT Corporation, 2008.

Table 8: SafetyAnalyst's SPFs for Intersections (Fatal and Injury Crashes)

Site subtype Code	Site subtype Description	State	Regression coefficients LogIntercept (α)	Regression coefficients LogAADTmaj (β_1)	Regression coefficients LogAADT min (β_2)	Over - dispersion Parameter (k)	R_{FT}^2 (%)	No. of Sites	Max $AADT_{maj}$ (veh/day)	Max $AADT_{min}$ (veh/day)
Rural										
201	Rural 3-leg with minor-road STOP control	MN	-9.35	0.71	0.21	1.23	9.1	1,706	28,500	27,000
202	Rural 3-leg with all-way STOP control	MN	-10.02	1.27	-0.22	0.89	24.8	41	25,300	6,803
203	Rural 3-leg with signal control	MN	-7.83	0.75	0.14	0.5	21.5	136	36,400	11,500
204	Rural 4-leg with minor-road STOP control	MN	-9.36	0.66	0.4	0	14.6	2,114	35,500	26,700
205	Rural 4-leg with all-way STOP control	MN	-10.02	1.27	-0.22	0.89	24.8	41	25,300	6,803
206	Rural 4-leg with signal control	MN	-7.83	0.75	0.14	0.5	21.5	136	36,400	11,500
Urban										
251	Urban 3-leg with minor-road STOP control	MN	-8.45	0.49	0.39	1.23	8.1	397	68,000	18,900
252	Urban 3-leg with all-way STOP control	MN	-10.02	1.27	-0.22	0.89	24.8	41	25,300	6,803
253	Urban 3-leg with signal control	MN	-10.22	0.91	0.21	0.27	36.2	33	50,000	25,807
254	Urban 4-leg with minor-road STOP control	MN	-4.35	0.29	0.19	0.99	5.7	333	58,870	81,000
255	Urban 4-leg with all-way STOP control	MN	-10.02	1.27	-0.22	0.89	24.8	41	25,300	6,803
256	Urban 4-leg with signal control	MN	-5.11	0.49	0.16	0.3	29.5	418	75,000	81,000

ITT Corporation, 2008.

The study examined the impact of two left turn priority treatments, which were flashing advanced green (FAG) and left turn green arrow (LTGA), on left turn collisions. These treatments were implemented at 35 intersections in the city of Toronto. Two types of collisions were investigated, left turns with and without side impact. The results indicated that there was an insignificant difference in the impact of the left turn priority treatments on both types of crashes.

Lord and Persaud (2003) conducted a study that related SPFs to transportation planning models. They noted that traffic safety is not usually accounted for when agencies are conducting a planning analysis to remodel, build, upgrade or modify their facilities. Five-year intersection data from Canada were used. Models were developed and statistical measures such as the over dispersion parameter, were calculated, and conclusions were made from the results. The SPFs developed for the study were applied to two sample networks created with the help of a transportation planning software package. The research showed that it is possible to make estimation for traffic safety at the planning stage of a project. This will allow users to take safety into consideration when designing and possibly create alternatives to change existing designs for more comprehensive projects or development. The study also indicated that there are limitations when applying the SPFs to computerized transportation networks. The study concluded that, although it is possible to predict or estimate crashes on digital transportation networks, the accuracy of prediction relies greatly on how precise the traffic flow estimates are.

Jonsson et al. (2007) performed an SPF study that took into consideration the type and severity of crashes and—most important—the causal factors for these crashes. The study was conducted for intersections on rural four-lane highways in the state of California. Four collision types were tested in the study: opposite-direction, same-direction, intersecting-direction and single-vehicle crashes. In addition, a set of data from the state of New York was used, with the same parameters, to analyze the severity distribution of crash types. The data for California included 1,084 intersections on four-lane rural highways, and that from New York included 675 intersections, mainly stop controlled or without any control. Generalized linear modeling was performed with the data after quality analysis. Two model forms were estimated with the variables seen in Equations 29 and 30:

$$N_{Acc} = AADT_{major}^{\beta_1} \; x \; AADT_{\min or}^{\beta_2} \; x \; e^{\beta_0+\beta_3 x_3+\beta_4 x_4+\ldots+\beta_n x_n} \qquad \text{(Eq. 29)}$$

$$N_{Acc} = (AADT_{major} + AADT_{\min or})^{\beta_1} \; x \; e^{\beta_0+\beta_2 x_2+\beta_3 x_3+\ldots+\beta_n x_n} \qquad \text{(Eq. 30)}$$

where

N_{Acc} = predicted number of crashes/yr at intersections
$AADT_{major}$ = AADT on major road
$AADT_{minor}$= AADT traffic flow on minor road
B_i = model parameters
X_i = variables that describe the intersections (such as terrain, lighting, left turn, number of though lanes and divided or undivided, among others).

The two different models are different representations of the traffic flow. The first represents the AADT of major and minor roads as separate variables, but in the second model they are represented as one variable by the sum of the major and minor roads AADTs. Results showed that the first model performed better for the multiple-vehicle crashes and the second model fitted better for the single-vehicle crashes. In addition, the appropriate predictor variables differed depending on the crash type. This study is also of interest as it incorporated additional parameters to those in the suggested SPFs now included in SafetyAnalyst and therefore could lead to possible future SPF research for the state of Virginia.

Persaud and Nguyen (1998) conducted a study on signalized intersections in Ontario Canada. They developed aggregate and disaggregate models to estimate safety performance of three- and four-leg intersections in which crash severity (injury and PDO), environmental class (semi-urban and rural) and time period (daily, weekday morning peak and weekday afternoon peak) were considered in the analysis. An important aspect of that study is that it supplemented the existing models used for estimating SPFs instead of replacing them because it took into consideration features that were generally not considered in the then existing developed models. Two model levels were considered for the study. Level 1 was based on the sum of AADTs for all approaches, with separate estimates for rear-end, right angle and turning movement crashes. At this level, the equations were adjusted for three- and four-leg intersections by crash severity for all combined impact types and also separately for the three major impact types, which were angle, rear-end and turning movement. In addition, models were further separated by time period (daily, weekday, morning and afternoon peak) and for four-leg intersections, which were also classified by environment class, such as semi-urban and rural. Level 2 allowed estimates to be obtained for specific crash patterns that were defined by movements of the vehicles involved before collision, and the same were estimated as a function of the flows that were relevant to each of the patterns. For this level, models were estimated for four-leg intersections for 12 multi-vehicle and three single-vehicle patterns that were described by the movements of involved vehicles before collision. The developed models were intended to estimate the parameters P and d shown in Equations 31 and 33.

The safety of the intersection was estimated using the long-term mean based on the EB approach. The long term mean (m) was obtained by combining crash count (x) of an intersection in the most recent years (n) with the estimates of the expected annual number of crashes (P) as shown in Equation 31. W_1 and W_2 in Equations 31 through 33 represent the weights estimated from the mean and variance of the regression estimates

$$m = W_1(x) + W_2(P) \qquad \text{(Eq. 31)}$$

$$W_1 = \frac{P}{d + nP} \qquad \text{(Eq. 32)}$$

$$W_2 = \frac{d}{d + nP} \qquad \text{(Eq. 33)}$$

$$d = \frac{P^2}{Var\left\{P\right\}} \qquad \text{(Eq. 34)}$$

To estimate the variance of m the following formula was used,

$$Var\left\{m\right\} = \frac{d+x}{n+(\frac{d}{P})^2} \qquad \text{(Eq. 35)}$$

In Equations 32 through 35, *P* and *d* represent the fundamental parameters.

Two models were selected for SPFs:

For Level 1 and single-vehicle Level 2: $P = \alpha S^{\beta}$ (Eq. 36)

For multi-vehicle in Level 2: $P = \alpha S_1^{\beta_1} S_2^{\beta_2}$ (Eq. 37)

where

P = expected number of crashes of a given type
α and β = regression parameters to be estimated
S (Level 1) = sum of all entering flows for a given time period for Level 1 analysis
S (Level 2) = sum of the daily through right or left turn flows for a given time period for Level 2 (single-vehicle) analysis
S_1 and S_2 = AADTs for small and large flows for a specific crash pattern in Level 2 (multi-vehicle) analysis.

The models in either level can be used in the EB procedure to provide estimates for intersections that need to be treated or for the evaluation of the effectiveness of safety countermeasures. It should be noted that the quality of the estimates for the study was strongly related to how the parameters were selected and used in the SPFs, and unlike other available road models, the ones presented in this study can be separated by time period, and crash pattern.

Persaud et al. (2002) conducted a study to demonstrate the complexity involved in the calibration of crash prediction models or SPFs for urban intersections. Toronto data for three- and four-leg signalized intersections were used to estimate the models for the study. The performance of these models was then compared with other models from Vancouver and California. The models from these places were recalibrated to fit Toronto by using the Interactive Highway Safety Design Model (IHSDM) and a calibration procedure as proposed by Harwood et al. (2000). The results varied significantly and were also mixed. The study noted that the calibration of models is not a simple task and due to the importance of the SPFs they must be properly calibrated. Several things must be accounted for when performing this procedure in order to obtain good quality data analysis. The first thing is to extract a large sample of high quality data. A software or program to link all the traffic, crash, and road characteristics data must exist because the same is usually kept stored in different databases. In addition, several years of crash data must be obtained in order to have a good amount of samples that account for variations. The actual process of model calibration is complicated; therefore careful attention must be paid when analyzing the same because of the importance of the outcomes of the study. The authors of the study made an exploratory analysis and it revealed that the relationship between the crashes and each covariate should be described either by the power function or the gamma function for all intersection types to be analyzed. Equations 38 through 40 are the selected model forms used in the study:

F_1 = Power, F_2 = Gamma $E(K) = \alpha F_1^{\beta_1} F_2^{\beta_2} e^{(\beta_3 F_2)}$ (Eq. 38)

F_1 = Gamma, F_2 = Power $E(K) = \alpha F_1^{\beta_1} F_2^{\beta_2} e^{(\beta_4 F_1)}$ (Eq. 39)

F_1 = Power, F_2 = Power $E(K) = \alpha F_1^{\beta_1} F_2^{\beta_2}$ (Eq. 40)

where

E (K) = expected annual number of crashes between 1990 and 1995
F_1, F_2 = average entering AADT of major and minor roads, respectively, for the period 1990 to 1995
α, β_1, β_2, β_3, β_4 = coefficients to be estimated.

An NB structure was used to analyze the models and the overdispersion parameter (γ) was analyzed using Equation 41.

$$\mathrm{Var(K)} = \frac{\mathrm{E(K)}^2}{\gamma} \qquad \text{(Eq. 41)}$$

Variance increases as γ decreases; therefore the value of γ can also be used to make a comparison for the goodness of fit of several models fitted to the same data. The larger the value of γ, the smaller the variance, therefore a more accurate model is given. The authors suggest that γ would be enough to calculate the goodness of fit index of any SPF but, if one desires to know how accurate the prediction estimate is, other measures should also be computed. The authors suggested using R^2_α as proposed by Miaou et al (1996), which is a dispersion parameter based $R^{2,}$ computed as shown in Equation 42.

$$\mathrm{R}^2_\alpha = 1 - \frac{\gamma_{\min}}{\gamma} \qquad \text{(Eq. 42)}$$

where

γ = overdispersion parameter for calibrated model
$\gamma_{\min}$ = smallest possible overdispersion parameter.

The authors suggested that a disaggregation by traffic volume is preferable than using only a single calibration factor, for that is what the IHSDM currently has. A recommendation is made to account for safety variation in traffic conditions over time by calibrating the models every two to three years as suggested by Harwood et al. (2000).

The Illinois Department of Transportation and the University of Illinois Urbana-Champaign conducted a research study to develop and implement SPFs for road segments and intersections in Illinois (Tegge et al., 2010). These SPFs were developed in a way suitable for easy implementation in SafetyAnalyst. The crash data (number of crashes and crash severity) and roadway data (number of lanes, traffic volume, area type and functional class) were collected and used for development of the SPFs. Seventeen peer groups were used for developing the SPFs for segments and eight for intersections. The intersections peer groups were minor leg stop control, all-way stop control, signalized, and undetermined for rural and urban segments separately. The SPFs for segments were developed using NB distribution for crashes and Poisson distribution for intersections. The SAS GENMOD procedure was used to develop the SPFs for a five-year analysis period from 2001 to 2005. The model form for the intersection SPFs is the same as that given in the *SafetyAnalyst User's Manual*. The SPFs were also developed for different crash severities, such as fatal crashes, type A injury crashes, type B injury crashes and fatal plus injury crashes. The EB method was used to determine the sites with the higher PSIs. Two analysis techniques were used to obtain the PSIs. The first considered segments and intersections as individual elements and the second used the sliding window approach. The site specific analysis treated each individual segment and intersection as a separate entity. Each segment is then compared with every other segment instead of having them grouped together. The sliding window approach defined a set length. The window lengths were 0.25 mile and 1 mile for urban and rural segments, respectively.

The largest impact on crash frequency was found to be the AADT and was therefore the only variable modeled as a logarithm (lnAADT). By doing this, the AADT accounted for most of the prediction whereas the rest of the variables refined the prediction further. Other variables used included access control, functional class, lane width, surface type, area type, speed limit, and median type. The study recommended that a multivariate analysis be conducted for such studies, to show how certain variables could contribute to the crashes. Other variables could include roadway lighting, weather and pavement conditions, and roadway geometry. The study also concluded that knowledge of roadway characteristics that increase the risk of fatal or injury crashes will facilitate the setting up of safety criteria that can help engineers in the designing of safer roadways. Further, knowledge of driver behaviors that lead to fatal and severe injury crashes can facilitate the training of enforcement officers to identify these behaviors.

The Colorado Department of Transportation (CDOT) (2009) conducted a study to develop SPFs for intersections in the state. Their model form is the same as that in SafetyAnalyst. The SPFs were developed for many categories based on the number of legs, divided, undivided, rural and urban, including urban four-lane divided signalized, six-lane divided signalized, urban three-leg signalized, two-lane undivided unsignalized and urban three-leg unsignalized. When a median or left-turn lane is present, a roadway is considered divided. The sites selected for the study reflected variability in traffic volume and geometry in order to have a diverse representation of intersections throughout the state. SPFs were developed for total and for fatal plus injury crash types. A five-year study period from 2000 through 2005 was used. Crash and AADT data were collected for development of the SPFs. CDOT used a NB error structure to develop the SPFs, and the EB procedure to estimate the expected safety performance of an intersection site for different safety management purposes. Overdispersion parameters were computed and used as a goodness of fit measure. According to their data, overdispersion parameters indicated that their models provided a reasonable fit to the Colorado data.

Results indicated that for signalized intersections, roads with six lanes on major approaches have more collisions than those with four lanes on major approaches. CDOT recommended that the SPFs should be recalibrated in the future using data from future years, as crash frequencies may change over time because of a variety of issues. The report also recommended that separate calibration factors should be developed for different regions and different topographies.

Research in Virginia

In Virginia, two other similar studies have recently been published. One by Garber et al. (2010) for two-lane roads and another by Hamidi et al. (2010) to identify high-crash sections on Virginia's primary system by developing a planning-level methodology. The study by Garber et al. developed SPFs for two-lane segments of 1 mile or less, and the study by Hamidi et al developed SPFs for longer segments of two-lane roads that can be used for corridor analysis.

Evaluation of the Recommended Minnesota SPFs

Figures 3 through 6 show representative graphs that were used to visually examine how well the Virginia data fitted the suggested Minnesota SPFs. Figures 3 and 4 are for urban four-leg signalized intersections and Figures 5 and 6 are for rural four-leg signalized intersections. These graphs suggest that the Minnesota SPFs do not fully represent the Virginia data. Tables 9 through 12 show the Freeman-Tukey R^2_{FT} coefficients computed for the different Minnesota SPFs using the Virginia data. The low Freeman-Tukey R^2_{FT} coefficients obtained and the visual inspection of the graphs suggested that a better fit to the Virginia data could be obtained by developing specific Virginia SPFs using Virginia data. It was therefore decided to develop specific SPFs for Virginia.

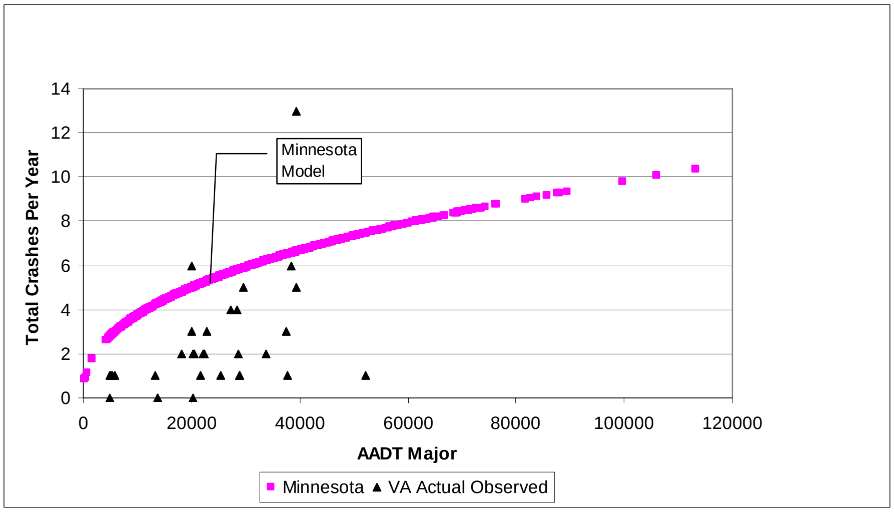

Figure 3: Total crashes per year vs. major AADT for urban 4-leg signalized intersections with minor AADT of 700

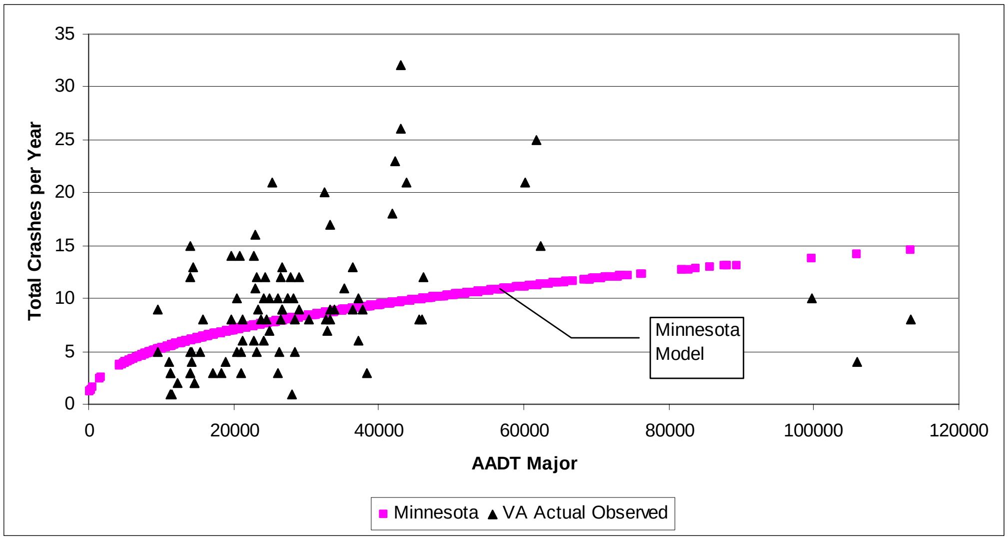

Figure 4: Total crashes per year vs. major AADT for urban 4-leg signalized intersections with minor AADT of 4500

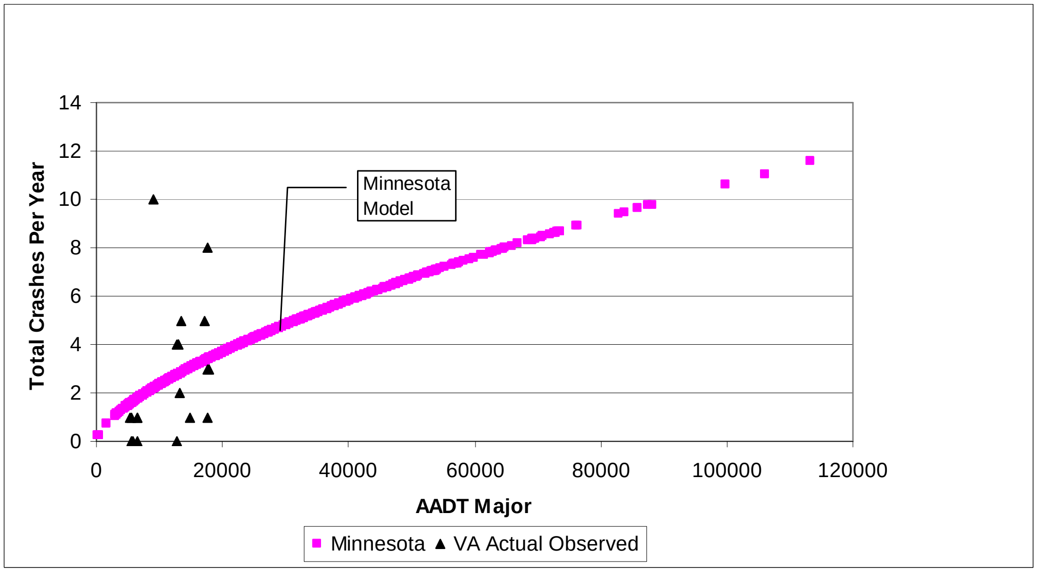

Figure 5: Total crashes per year vs. major AADT for rural 4-leg signalized intersections with minor AADT of 795

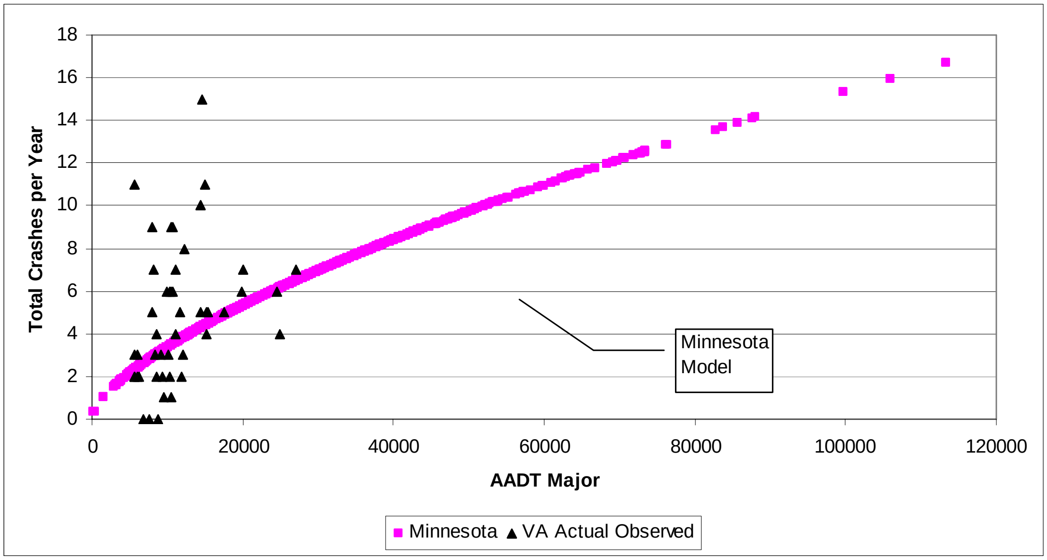

Figure 6: Total crashes per year vs. major AADT for rural 4-leg signalized intersections with minor AADT of 5000

Table 9: Minnesota SPFs for Urban FI Crashes and Corresponding R^2_{FT} Based on Virginia Data

Intersection Type	Minnesota FI SPFs	R^2_{FT} Based on Virginia Urban FI Crash Data (%)
Urban 4-Leg Signalized	$e^{-8.41} \times MajADT^{0.49} \times MinADT^{0.16}$	0.32
Urban 4-Leg Minor Stop Control	$e^{-4.77} \times MajADT^{0.59} \times MinADT^{0.49}$	0.08
Urban 3-Leg Signalized	$e^{-10.55} \times MajADT^{0.91} \times MinADT^{0.51}$	0.26
Urban 3-LegMinor Stop Control	$e^{-8.47} \times MajADT^{0.49} \times MinADT^{0.39}$	0.1

Table 10: Minnesota SPFs for Urban TOTAL crashes and Corresponding R^2_{FT} Based on Virginia Data

Type of Intersection	Minnesota SPFs	R^2_{FT} Based on Virginia Urban Total Crash Data (%)
Urban 4-Leg Signalized	$e^{-5.47} \times MajADT^{0.45} \times MinADT^{0.14}$	0.34
Urban 4-Leg Minor Stop Control	$e^{-5.46} \times MajADT^{0.67} \times MinADT^{0.16}$	0.22
Urban 3-Leg Signalized	$e^{-9.88} \times MajADT^{0.87} \times MinADT^{0.18}$	0.31
Urban 3-Leg Minor Stop Control	$e^{-5.33} \times MajADT^{0.34} \times MinADT^{0.28}$	0.1

Table 11: Minnesota SPFs for Rural TOTAL Crashes and Corresponding R^2_{FT} Based on Virginia Data

Type of Intersection	Minnesota SPFs	R^2_{FT} Based on Virginia Rural Total Crash Data (%)
Rural 4-Leg Signalized	$e^{-6.57} \times MajADT^{0.66} \times MinADT^{0.40}$	0.29
Rural 4-Leg Minor Stop Control	$e^{-8.76} \times MajADT^{0.62} \times MinADT^{0.47}$	0.13
Rural 3-Leg Signalized	$e^{-6.57} \times MajADT^{0.66} \times MinADT^{0.40}$	0.29
Rural 3-Leg Minor Stop Control	$e^{-8.58} \times MajADT^{0.71} \times MinADT^{0.41}$	-0.10

Table 12: Minnesota SPFs for Rural FI Crashes and Corresponding R^2_{FT} Based on Virginia Data

Type of Intersection	Minnesota SPFs	R^2_{FT} Based on Virginia Rural FI Crash Data (%)
Rural 4-Leg Signalized	$e^{-7.83} \times MajADT^{0.57} \times MinADT^{0.44}$	0.18
Rural 4-Leg Minor Stop Control	$e^{-9.86} \times MajADT^{0.66} \times MinADT^{0.40}$	0.10
Rural 3-Leg Signalized	$e^{-7.83} \times MajADT^{0.57} \times MinADT^{0.44}$	0.18
Rural 3-Leg Minor Stop Control	$e^{-9.88} \times MajADT^{0.71} \times MinADT^{0.41}$	0.01

Development and Evaluation of Specific Virginia SPFs

In keeping with the suggestion given in the *Safety Analyst User's Manual* , the model form used to develop the intersection SPFs is given in Equation 4 as:

$$\hat{k} = e^{\alpha} x \, MajAADT^{\beta_1} \; x \; MinAADT^{\beta_2}$$

where

$\hat{k}$ = predicted crash frequency per intersection per year
$MajAADT$ = AADT on the major road (veh/day)
$MinAADT$ = AADT on the minor road (veh/day)
α = intercept
β_1 = coefficient of mayor AADT
β_2 = coefficient of minor AADT.

The statewide SPFs developed for Virginia are given in Tables 13 through 16. Due to lack of data, the analysis for all-way stop intersections could not be undertaken. These tables also give the Freeman-Tukey R^2_{FT} coefficient for each of the Virginia SPFs and the corresponding Minnesota SPF and Freeman-Tukey R^2_{FT} based on the Virginia data. The R^2_{FT} coefficients obtained indicate that the Virginia-specific SPFs fit the Virginia data better than the suggested Minnesota SPFs, for all types of intersections and crash severity except those for FI crashes on urban three-leg signalized, rural four-leg signalized and rural four-leg minor stop control intersections, where the corresponding R_{FT}^2 values are similar. In Table 15, it can be seen that the Minnesota R^2_{FT} value is negative for the rural three-leg minor stop control intersections. The negative R_{FT}^2 value is possible because these calculations were not performed on the same data points that were used to create the Minnesota SPFs (Miller, 2009).

Table 13: SPF Models for Urban TOTAL crashes and R^2_{FT} results for Virginia Statewide (VDOT-maintained roads)

Site	SPF model with TOTAL Crash values		R^2_{FT} TOTAL Crash Data	
	Virginia Statewide	Minnesota	VA	MN
Urban 4-Leg Signalized	$e^{-7.66} \times MajADT^{0.67} \times MinADT^{0.33}$	$e^{-3.47} \times MajADT^{0.42} \times MinADT^{0.14}$	0.56	0.34
Urban 4-Leg Minor Stop Control	$e^{-6.07} \times MajADT^{0.46} \times MinADT^{0.33}$	$e^{-5.46} \times MajADT^{0.67} \times MinADT^{0.16}$	0.32	0.22
Urban 3-Leg Signalized	$e^{-6.24} \times MajADT^{0.66} \times MinADT^{0.21}$	$e^{-9.83} \times MajADT^{0.97} \times MinADT^{0.18}$	0.37	0.31
Urban 3-Leg Minor Stop Control	$e^{-5.47} \times MajADT^{0.49} \times MinADT^{0.20}$	$e^{-5.33} \times MajADT^{0.34} \times MinADT^{0.28}$	0.23	0.10

Table 14: SPF Models for Urban FI crashes and R^2_{FT} results for Virginia Statewide (VDOT-maintained roads)

Site	SPF model with FI Crash values		R^2_{FT} FI Crash Data (%)	
	Virginia Statewide	Minnesota	VA	MN
Urban 4-Leg Signalized	$e^{-8.83} \times MajADT^{0.68} \times MinADT^{0.36}$	$e^{-5.41} \times MajADT^{0.49} \times MinADT^{0.16}$	0.41	0.32
Urban 4-Leg Minor Stop Control	$e^{-7.69} \times MajADT^{0.30} \times MinADT^{0.37}$	$e^{-4.33} \times MajADT^{0.49} \times MinADT^{0.49}$	0.19	0.08
Urban 3-Leg Signalized	$e^{-8.43} \times MajADT^{0.71} \times MinADT^{0.63}$	$e^{-10.66} \times MajADT^{0.81} \times MinADT^{0.61}$	0.26	0.26
Urban 3-Leg Minor Stop Control	$e^{-7.46} \times MajADT^{0.38} \times MinADT^{0.21}$	$e^{-8.48} \times MajADT^{0.49} \times MinADT^{0.39}$	0.13	0.10

Table 15: SPF Models for Rural TOTAL Crashes and R^2_{FT} Results for Virginia Statewide (VDOT-maintained roads)

Site	SPF model with TOTAL Crash values		R^2_{FT} TOTAL Crash Data	
	Virginia Statewide	Minnesota	VA	MN
Rural 4-Leg Signalized	$e^{-6.96} \times MajADT^{0.67} \times MinADT^{0.23}$	$e^{-6.37} \times MajADT^{0.66} \times MinADT^{0.20}$	0.321	0.290
Rural 4-Leg Minor Stop Control	$e^{-3.49} \times MajADT^{0.33} \times MinADT^{0.39}$	$e^{-8.96} \times MajADT^{0.68} \times MinADT^{0.47}$	0.167	0.132
Rural 3-Leg Signalized	$e^{-7.28} \times MajADT^{0.68} \times MinADT^{0.33}$	$e^{-6.37} \times MajADT^{0.66} \times MinADT^{0.20}$	0.305	0.291
Rural 3-Leg Minor Stop Control	$e^{-4.33} \times MajADT^{0.34} \times MinADT^{0.61}$	$e^{-8.78} \times MajADT^{0.71} \times MinADT^{0.61}$	0.104	-0.102

Table 16: SPF Models for Rural FI crashes and R^2_{FT} results for Virginia Statewide (VDOT-maintained roads)

Site	SPF model with FI Crash values		R^2_{FT} TOTAL Crash Data	
	Virginia Statewide	Minnesota	VA	MN
Rural 4-Leg Signalized	$e^{-8.71} \times MajADT^{0.58} \times MinADT^{0.66}$	$e^{-7.83} \times MajADT^{0.57} \times MinADT^{0.44}$	0.181	0.181
Rural 4-Leg Minor Stop Control	$e^{-6.69} \times MajADT^{0.39} \times MinADT^{0.42}$	$e^{-9.38} \times MajADT^{0.66} \times MinADT^{0.40}$	0.098	0.097
Rural 3-Leg Signalized	$e^{-8.71} \times MajADT^{0.56} \times MinADT^{0.66}$	$e^{-7.83} \times MajADT^{0.57} \times MinADT^{0.44}$	0.170	0.180
Rural 3-Leg Minor Stop Control	$e^{-5.34} \times MajADT^{0.34} \times MinADT^{0.52}$	$e^{-9.28} \times MajADT^{0.71} \times MinADT^{0.21}$	0.048	0.012

Figures 7 through 10 show visual representations of how well the Virginia SPFs fit the Virginia data in comparison with the suggested Minnesota SPFs. In general, the Virginia SPFs tend to fit the Virginia data better than the Minnesota SPFs, although both sets of SPFs tend to have similar fits at low volumes ($AADT_{major} < 2000$), except for the SPF for total crashes on urban four-leg signalized intersections shown in Figure 7. The primary reason the Minnesota SPFs do not fit the Virginia data as well as the Virginia SPFs may be the dissimilarities of the roadside environment and the characteristics of the different databases.

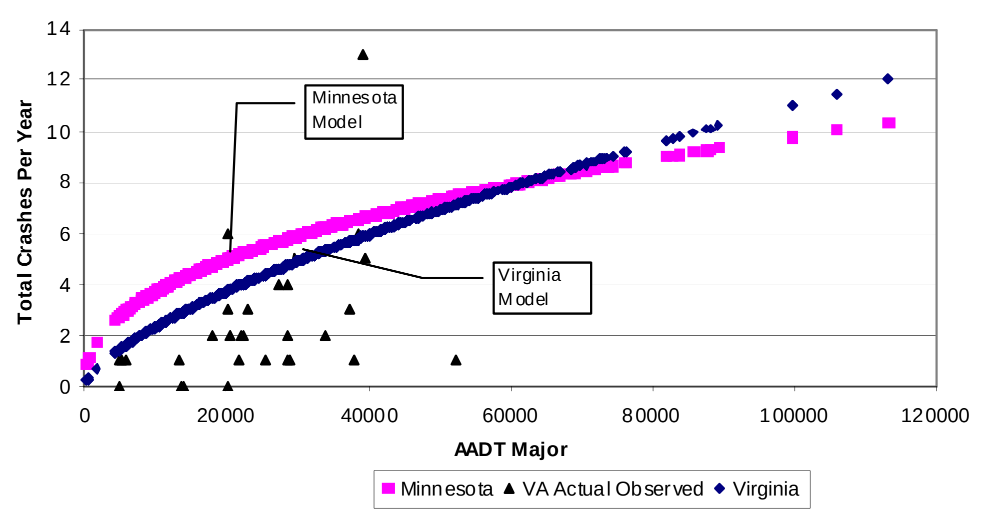

Figure 7: Total crashes per year vs. major AADT for urban 4-leg signalized intersections with minor AADT of 700

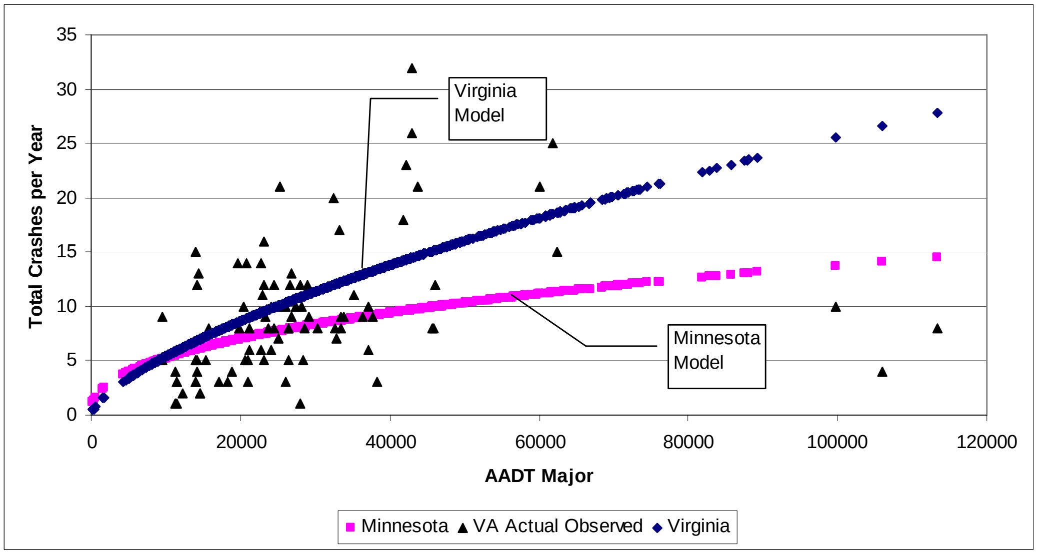

Figure 8: Total crashes per year vs. major AADT for urban 4-leg signalized intersections with minor AADT of 8000

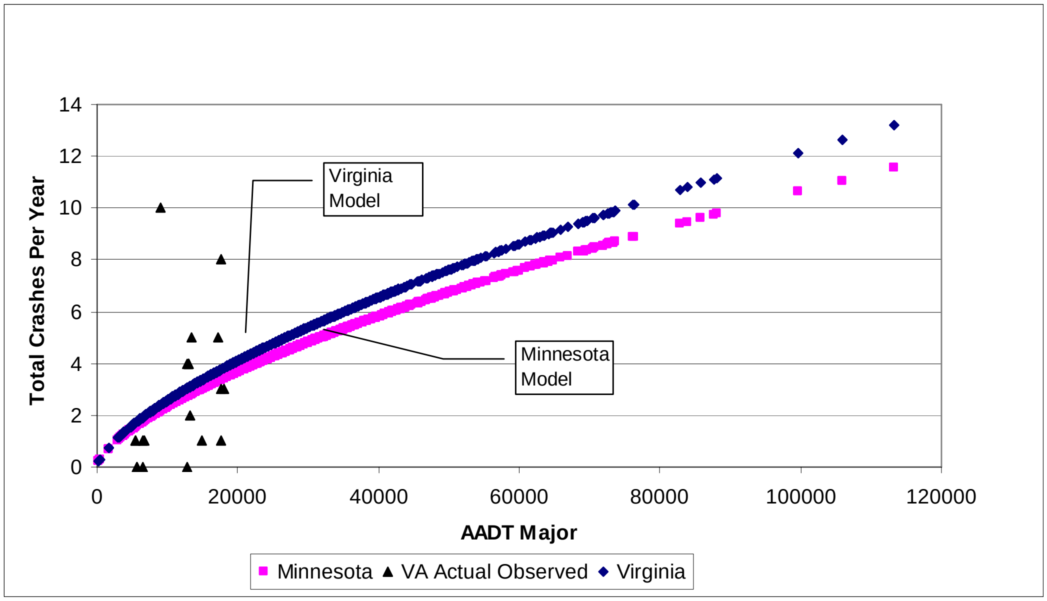

Figure 9: Total crashes per year vs. major AADT for rural 4-leg signalized intersections with minor AADT of 79

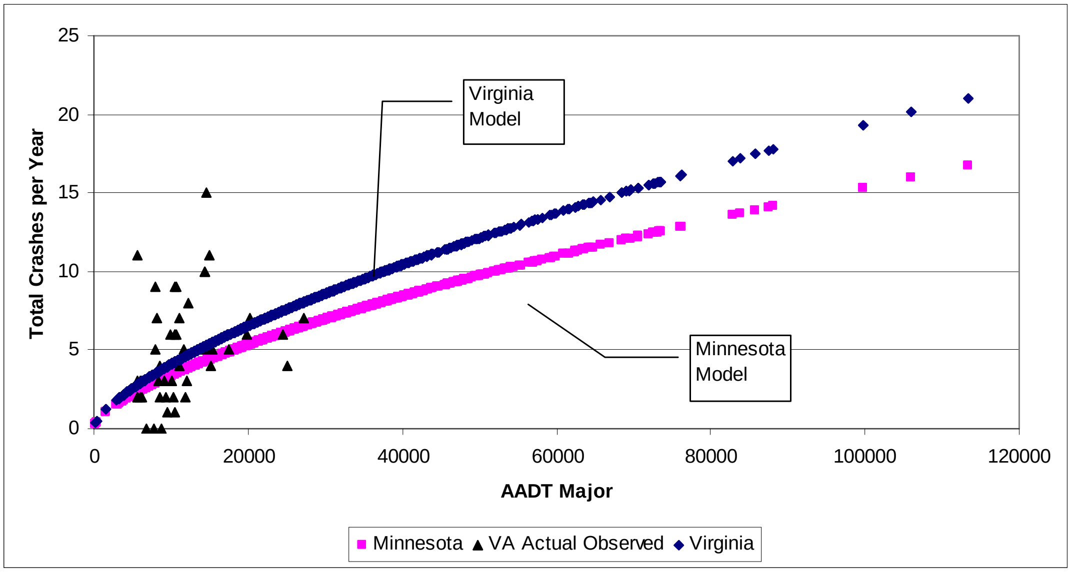

Figure 10: Total crashes per year vs. minor AADT for rural 4-leg signalized intersections with major AADT of 5000

As discussed in the Methodology section, in addition to the statewide Virginia SPFs, specific SPFs were developed for each operational region to consider the different topographical characteristics that exist across Virginia. The complete set of SPFs together with the associated *p* values for the regression coefficients are shown in Tables A-1 and A-2 of Appendix A. All *p* values are less than 0.05, with most being less than 0.0001, except for some of the rural four-leg signalized intersections regional specific SPFs. These *p* values indicate that the estimated coefficients are statistically significant at the 95% confidence level or better. A possible reason for higher *p* values for a small number of SPFs may be the sample size used for developing these SPFs.

To test the transferability and fit of the Virginia statewide specific SPFs, several statistical parameters were determined for the 70% (estimation) data set and the 30% (validation) data set separately. The corresponding values for each of these parameters were then compared. The results are shown in Tables 17 and 18 for urban and rural intersections, respectively. The results for the regional SPFs are shown in Tables A-3 through A-8 of Appendix A. The results indicate that the developed models are transferable to the 30% validation data set. For example, the MSE values for the 70% estimation data are similar to the MSPE values for the 30% validation data. In addition, the mean prediction bias MPB values for the 30 % validation data are close to zero (-0.76 ≤ MPB ≥ -0.004) in Table 17 and (-0.067 ≤ MPB ≥ 0.0513) in Table 18.

Table 17: Goodness of Fit Results for Urban Statewide SPFs

Data		Estimation data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Urban 4-Leg Signalized	Total VA	41.150	0.529	0.557	-0.760	4.329	38.490	0.575
	Total MN	68.636	0.506	0.336	-3.145	5.421	68.156	0.315
	FI VA	7.043	0.385	0.406	-0.458	1.938	7.671	0.475
	FI MN	7.702	0.372	0.324	-0.316	2.124	8.981	0.376
Urban 4-Leg Minor Stop Control	Total VA	2.238	0.315	0.313	-0.034	0.897	2.383	0.292
	Total MN	2.510	0.287	0.215	0.091	0.982	2.730	0.182
	FI VA	0.530	0.194	0.193	-0.004	0.432	0.533	0.194
	FI MN	0.560	0.182	0.080	0.128	0.522	0.577	0.052
Urban 3-Leg Signalized	Total VA	24.900	0.375	0.370	-0.645	3.519	27.591	0.369
	Total MN	29.322	0.365	0.308	-2.238	3.661	33.079	0.272
	FI VA	4.467	0.275	0.259	-0.185	1.527	4.875	0.262
	FI MN	4.528	0.267	0.261	-0.294	1.526	4.937	0.261
Urban 3-Leg Minor Stop Control	Total VA	1.854	0.254	0.230	-0.043	0.893	2.038	0.239
	Total MN	2.388	0.237	0.104	-0.541	0.902	2.600	0.107
	FI VA	0.428	0.151	0.133	-0.021	0.431	0.476	0.157
	FI MN	0.478	0.140	0.097	-0.184	0.385	0.537	0.104

Table 18: Goodness of Fit Results for Rural Statewide SPFs

Data		Estimation Data 70%			Validation Data 30%			
Subtype	Site	MSE	r^2	R^2_{FT}	MPB	MAD	MSPE	R^2_{FT}
Rural 4-Leg Signalized	Total VA	10.990	0.353	0.321	0.513	2.210	10.070	-0.073
	Total MN	12.400	0.339	0.290	-0.154	2.071	8.460	0.035
	FI VA	2.350	0.196	0.181	0.045	1.189	2.600	-0.034
	FI MN	2.400	0.188	0.181	-0.043	1.164	2.420	0.004
Rural 4-Leg Minor Stop Control	Total VA	1.090	0.182	0.167	-0.067	0.794	1.190	0.171
	Total MN	1.190	0.167	0.132	-0.348	0.774	1.320	0.115
	FI VA	0.480	0.112	0.098	-0.022	0.504	0.530	0.110
	FI MN	0.500	0.104	0.097	-0.158	0.459	0.560	0.093
Rural 3-Leg Signalized	Total VA	5.490	0.328	0.305	-0.010	1.651	5.760	0.179
	Total MN	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	FI VA	1.450	0.181	0.170	-0.041	0.902	1.710	0.099
	FI MN	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rural 3-Leg Minor Stop Control	Total VA	0.690	0.144	0.104	-0.008	0.613	0.730	0.102
	Total MN	0.890	0.141	-0.102	-0.404	0.555	0.940	-0.104
	FI VA	0.250	0.071	0.048	-0.009	0.345	0.260	0.048
	FI MN	0.270	0.068	0.012	-0.144	0.270	0.290	0.003

Pruning of Virginia-Specific SPFs

A total of 64 SPFs were initially developed using the appropriate data for Virginia as shown in Tables A-1 and A-2 of Appendix A. Considering that not all regional models might be necessary, the pruning process described in the methodology section was carried out to prune the number of SPFs to the minimum effective number as seen in Tables 19 and 20 for urban and rural intersections, respectively. The pruning process resulted in 19 SPFs for urban sites and 15 for rural sites. To facilitate the use of the correct SPF for a specific type of intersection located in a specific region, the lists of the appropriate SPFs to be used are given in Tables B-1 and B-2 of Appendix B for the urban and rural intersections, respectively.

As can be seen in Tables 19 and 20 and Tables A-1 and A-2 of Appendix A, there are some trends worth discussing for the benefit of the study and possible future research. With regards to the three different operational regions, the Western region retained many more of the specific regional urban SPFs than any other region. For example, the Western regional SPFs were retained for all urban intersection sites whereas for the Eastern region, the only SPFs retained were those for urban four-leg signalized FI crashes and urban four-leg minor stop control for total and FI crashes. Similarly, the only urban SPF retained for the Northern region was that for urban four-leg minor stop control for total crashes. For the rural intersection sites, all of the Western regional SPFs were retained except those for rural three-leg signalized total and FI crashes and rural four-leg minor stop control FI crashes. The majority of the Eastern region rural SPFs were discarded except those for rural four-leg signalized total and FI crashes while for the Northern region all regional SPFs were discarded.

The Western region retained more specific regional SPFs than the other two regions. This suggests that the intersections in the Western region exhibit more unique characteristics than those for the other regions. This may be due to the more mountainous terrain in the Western region compared to those in the Eastern and Northern regions. This supports the philosophy of developing specific SPFs based on the topography of different regions.

Site Prioritization

To illustrate the benefits of using the EB method to prioritize intersection sites for safety improvements, the top 25 urban sites from the Bristol and Northern Virginia districts were identified by using crash rates, critical crash ratio and the EB method. The PSI for each site identified was then determined. The results obtained are shown in Tables 21 and 22 for the Bristol and the Northern Virginia districts, respectively. The results indicate that for the Northern Virginia District, the PSIs for the top 25 sites are 2.58, 13.17, and 274.40 crashes per year, and for the Bristol District 4.32, 6.46, and 14.96 crashes per year for the crash rates, critical crash ratio, and EB methods, respectively. The important thing in Tables 21 and 22 is the sum of the PSI columns ranked by the three methods. The sum of each of the PSIs for the crash rate and critical crash ratio method is lower than that for the EB method. These results suggest that the use of the EB method in the planning process will identify intersection sites with the highest PSIs and, therefore, where detailed assessments to determine feasible and effective safety treatments should be undertaken.

Table 19: MSPE Values for Virginia Urban Statewide and Urban Regional SPFs Used for Pruning

Data		**Pruning**				
Subtype	**Site**	**MSPE**	**$[MSPE_{VA}-MSPE_{OR}]^{1}$****	**$[abs(MSPE_{VA}-MSPE_{OR})]^{2}$**	**$[abs(MSPE_{VA}-MSPE_{OR})/MSPE_{VA}]^{3}$*****	**Retain/Discard**
Urban 4-Leg Signalized	**Total VA**	**38.49***				
	Northern	44.86	-6.37	6.37	0.165497532	Discard
	Western	**17.91***	20.58	20.58	0.534684334	Retain
	Eastern	37.45	1.04	1.04	0.027020005	Discard
	FI VA	**7.671***				
	Northern	9.5	-1.829	1.829	0.238430452	Discard
	Western	**5.17***	2.501	2.501	0.326033112	Retain
	Eastern	**5.41***	2.261	2.261	0.294746448	Retain
Urban 4-Leg Minor Stop Control	**Total VA**	2.3834				
	Northern	**2.02***	0.3634	0.3634	0.15247126	Retain
	Western	**1.05***	1.3334	1.3334	0.559452882	Retain
	Eastern	**1.15***	1.2334	1.2334	0.517496014	Retain
	FI VA	**0.5327***				
	Northern	0.48	0.0527	0.0527	0.098929979	Discard
	Western	**0.33***	0.2027	0.2027	0.380514361	Retain
	Eastern	**0.36***	0.1727	0.1727	0.324197485	Retain
Urban 3-Leg Signalized	**Total VA**	**27.5911***				
	Northern	26.87	0.7211	0.7211	0.026135239	Discard
	Western	**24.41***	3.1811	3.1811	0.115294425	Retain
	Eastern	38.78	-11.1889	11.1889	0.405525695	Discard
	FI VA	**4.8754***				
	Northern	4.48	0.3954	0.3954	0.081101038	Discard
	Western	**3.39***	1.4854	1.4854	0.304672437	Retain
	Eastern	5.86	-0.9846	0.9846	0.20195266	Discard
Urban 3-Leg Minor Stop Control	**Total VA**	**2.0379***				
	Northern	2.19	-0.1521	0.1521	0.074635654	Discard
	Western	**1.64***	0.3979	0.3979	0.195250012	Retain
	Eastern	2.23	-0.1921	0.1921	0.094263703	Discard
	FI VA	**0.4756***				
	Northern	0.5	-0.0244	0.0244	0.051303616	Discard
	Western	**0.38***	0.0956	0.0956	0.201009251	Retain
	Eastern	0.5	-0.0244	0.0244	0.051303616	Discard

[1] Difference between mean square prediction error (MSPE) of Virginia statewide model and OR model.

[2] Absolute value of the difference between Virginia statewide model MSPE and operational region model MSPE.

[3] Absolute value of the difference between Virginia statewide model MSPE and operational region model MSPE. divided by the Virginia statewide MSPE for comparison.

*Retained SPFs.

**Discarded if value is negative.

*** Discarded if less than 0.1.

Table 20: MSPE Values for Virginia Rural Statewide and Rural Regional SPFs Used for Pruning

Data		**Pruning**				
Subtype	**Site**	**MSPE**	**[MSPE$_{VA}$-MSPE$_{OR}$][1]****	**[abs(MSPE$_{VA}$-MSPE$_{OR}$)][2]**	**[abs(MSPE$_{VA}$-MSPE$_{OR}$)/MSPE$_{VA}$][3]*****	**Retain/Discard**
Rural 4-Leg Signalized	**Total VA**	**10.07***				
	Northern	34.22	-24.15	24.15	2.398212512	Discard
	Western	**6.05***	4.02	4.02	0.399205561	Retain
	Eastern	**5.12***	4.95	4.95	0.491559086	Retain
	FI VA	**2.6***				
	Northern	9.76	-7.16	7.16	2.753846154	Discard
	Western	**1.59***	1.01	1.01	0.388461538	Retain
	Eastern	**1.37***	1.23	1.23	0.473076923	Retain
Rural 4-Leg Minor Stop Control	**Total VA**	**1.19***				
	Northern	1.64	-0.45	0.45	0.378151261	Discard
	Western	**1.02***	0.17	0.17	0.142857143	Retain
	Eastern	1.14	0.05	0.05	0.042016807	Discard
	FI VA	**0.53***				
	Northern	0.52	0.01	0.01	0.018867925	Discard
	Western	0.48	0.05	0.05	0.094339623	Discard
	Eastern	0.49	0.04	0.04	0.075471698	Discard
Rural 3-Leg Signalized	**Total VA**	**5.76***				
	Northern	14.75	-8.99	8.99	1.560763889	Discard
	Western	6.74	-0.98	0.98	0.170138889	Discard
	Eastern	6.26	-0.5	0.5	0.086805556	Discard
	FI VA	**1.71***				
	Northern	2.12	-0.41	0.41	0.239766082	Discard
	Western	4.03	-2.32	2.32	1.356725146	Discard
	Eastern	1.57	0.14	0.14	0.081871345	Discard
Rural 3-Leg Minor Stop Control	**Total VA**	**0.73***				
	Northern	0.93	-0.2	0.2	0.273972603	Discard
	Western	**0.53***	0.2	0.2	0.273972603	Retain
	Eastern	0.69	0.04	0.04	0.054794521	Discard
	FI VA	**0.26***				
	Northern	0.3	-0.04	0.04	0.153846154	Discard
	Western	**0.23***	0.03	0.03	0.115384615	Retain
	Eastern	0.27	-0.01	0.01	0.038461538	Discard

[1] Difference between mean square prediction error (MSPE) of Virginia statewide model and OR model.

[2] Absolute value of the difference between Virginia statewide model MSPE and operational region model MSPE.

[3] Absolute value of the difference between Virginia statewide model MSPE and operational region model MSPE. divided by the Virginia statewide MSPE for comparison.

*Retained SPFs.

** Discarded if value is negative.

*** Discarded if less than 0.1.

Table 21: PSIs for Top 25 Sites in District 1 Urban (Bristol)

FI Crashes	Ranking Based on Crash Rates			Ranking Based on Crash Ratio			Ranking Based on EB Method	
Rank	**Intersection Node**	**Crash Rate[1]**	**PSI[2]**	**Intersection Node**	**Crash Ratio[3]**	**PSI**	**Intersection Node**	**PSI**
1	596726	2.2112	0.0000	651193	3.9672	0.0000	596095	2.1413
2	606469	2.0079	0.0000	606238	3.9298	0.6297	596393	0.8787
3	706818	1.2504	0.0000	651075	3.1264	0.0000	651130	0.8453
4	651193	1.1550	0.0000	596726	2.9227	0.0000	596701	0.7112
5	651075	0.9369	0.0000	606469	2.8039	0.0000	651802	0.6929
6	606238	0.8382	0.6297	651233	2.5831	0.3612	636331	0.6726
7	651807	0.7089	0.0000	651130	2.2718	0.8453	596395	0.6579
8	651233	0.6068	0.3612	706818	2.2555	0.0000	596937	0.6415
9	651230	0.5990	0.0000	651230	2.0301	0.0000	606238	0.6297
10	651783	0.5756	0.0000	651210	1.8882	0.4747	661033	0.6061
11	636093	0.4960	0.0000	636331	1.7913	0.6726	596372	0.5417
12	651274	0.4475	0.0000	651807	1.6847	0.0000	636372	0.4808
13	651130	0.4179	0.8453	651805	1.5814	0.0000	651210	0.4747
14	651210	0.3918	0.4747	651223	1.5627	0.3589	636491	0.4649
15	636331	0.3393	0.6726	651783	1.5009	0.0000	596420	0.4633
16	651223	0.3363	0.3589	596095	1.4865	2.1413	596403	0.4579
17	606232	0.3331	0.0000	636405	1.4769	0.0000	651603	0.4531
18	651127	0.3053	0.0000	661033	1.4555	0.6061	636056	0.4351
19	651999	0.3048	0.0000	596353	1.4215	0.3717	712033	0.4110
20	596449	0.2962	0.0000	636093	1.3782	0.0000	704691	0.4102
21	636405	0.2811	0.0000	651879	1.3192	0.0000	651838	0.4100
22	651883	0.2698	0.0000	651274	1.2975	0.0000	651894	0.3878
23	596353	0.2686	0.3717	651127	1.2972	0.0000	596353	0.3717
24	651805	0.2663	0.0000	651999	1.2959	0.0000	651233	0.3612
25	661033	0.2500	0.6061	596449	1.2702	0.0000	651889	0.3601
		sum	4.3202		sum	6.4615	sum	14.9606

[1] Number of crashes per year per 1,000,000 total approach volume.

[2] Potential for safety improvement (crashes /yr), the difference between the EB-adjusted long-term crashes and the SPF-estimated crashes.

[3] Ratio of actual crash rate to critical crash rate.

Table 22: PSIs for Top 25 Sites in District 9 Urban (Northern Virginia District)

FI Crashes	Ranking Based on Crash Rates			Ranking Based on Crash Ratio			Ranking Based on EB Method	
Rank	Intersection Node	Crash Rate[1]	PSI[2]	Intersection Node	Crash Ratio[3]	PSI	Intersection Node	PSI
1	718192	19.1841	0.0000	718192	25.7523	0.0000	264119	15.0122
2	702946	17.8194	0.0000	547722	15.2371	1.1175	263375	14.0091
3	271531	6.4846	0.0000	263628	10.2794	0.0000	278648	13.7239
4	263628	5.2858	0.0000	263728	10.0092	0.0000	276819	13.1395
5	263728	4.2215	0.0000	719754	9.5274	0.9444	263290	13.0743
6	266955	3.5294	0.0000	702946	7.9268	0.0000	722678	12.7897
7	547722	3.4932	1.1175	263403	7.7252	0.5184	264725	11.8671
8	702612	3.0441	0.0000	704237	7.7175	0.7648	267028	11.6627
9	273886	2.9539	0.0000	263729	7.4681	0.0000	265204	11.5925
10	716747	2.7632	0.0000	271531	7.2327	0.0000	274766	11.5679
11	263626	2.7139	0.0000	263135	6.6458	1.8068	263249	11.3372
12	269485	2.6567	0.0000	716747	6.4461	0.0000	547044	11.0769
13	728954	2.6344	0.0000	266955	5.6657	0.0000	549349	10.7180
14	263729	2.5208	0.0000	546138	5.2003	3.1028	268210	10.5630
15	546988	2.1922	0.0000	547544	5.1924	3.2529	263347	10.4257
16	274338	2.1446	0.0000	263626	5.0389	0.0000	276351	10.2313
17	429308	2.1354	0.0000	269485	4.9897	0.0000	428167	10.0064
18	720401	2.1197	0.0000	728954	4.9702	0.0000	264344	9.8789
19	267295	2.0954	0.0000	548686	4.9572	0.3621	277764	9.1554
20	267536	2.0874	0.0000	711601	4.7985	0.4440	263467	8.9259
21	265938	2.0484	0.0000	266970	4.7730	0.0000	263090	8.9199
22	273354	2.0108	0.0000	546462	4.6856	0.3620	703414	8.8610
23	268345	1.9362	0.0000	265938	4.6726	0.0000	428629	8.7379
24	719754	1.9073	0.9444	720401	4.4833	0.0000	272219	8.5659
25	263403	1.9015	0.5184	728496	4.3666	0.4990	428544	8.5610
		Sum	2.5803		sum	13.1747	sum	274.4033

[1] Number of crashes per year per 1,000,000 total approach volume.

[2] Potential for safety improvement (crashes /yr), the difference between the EB-adjusted long-term crashes and the SPF-estimated crashes.

[3] Ratio of actual crash rate to critical crash rate.

CONCLUSIONS

- *The development of SPFs for intersections is necessary for Virginia because the SafetyAnalyst-suggested SPFs, which are based on Minnesota data, do not represent the Virginia data well.* Regarding the fit of the SPFs to Virginia data, the R^2_{FT} values shown in Tables 13 through 16 for Minnesota and Virginia indicate that the Virginia-specific SPFs fit the Virginia data better than the Minnesota models. This may be due to the dissimilarities of the roadside environment, such as difference in topography, and the characteristics of the different Virginia and Minnesota databases.

- *In some cases, the specific regional SPFs fit the regional data better than the statewide SPFs, suggesting that the specific SPFs should be considered for use when available.* These group divisions that have similar roadway characteristics and driver expectations in some cases tend to improve the fit.

- *In identifying intersection sites for safety improvements, it is clearly beneficial for the EB method to be used with the suitable SPFs, rather than a crash rate or critical ratio method.* Results of the site prioritization show a much higher potential for crash reduction when the EB method is used with the appropriate SPFs rather than a procedure based on crash rates or critical rates.

RECOMMENDATIONS

1. *VDOT's TED should use the Virginia-specific SPFs when using the SafetyAnalyst tools. The results of this study have shown that the Virginia-specific SPFs reflected the Virginia data better than the SafetyAnalyst-recommended Minnesota SPFs.*

2. *VDOT's TED should investigate the feasibility of using multiple SPFs in SafetyAnalyst.* If feasible, regional SPFs should be used. If it is not currently feasible to use multiple SPFs, VDOT's TED should ask that the FHWA include regional information in SafetyAnalyst so as to allow the use of regional SPFs. For the specific regional SPFs to be applied to Virginia and other states, the SafetyAnalyst tool should be capable of incorporating the necessary data that support the regional models.

3. *As soon as it is feasible to use regional SPFs, VDOT's TED should use the 19 SPFs developed for urban intersections and the 15 developed for rural intersections when using the tools in SafetyAnalyst.* Although the statewide SPFs are available for use by an analyst, the specific regional models included in the final set of SPFs will predict crashes better than the statewide SPFs. The regional analysis will not only ease the use of specific regional SPFs but will also be of benefit when predicting the potential for safety improvement of a specific site.

4. *For future similar SPF studies, VDOT's TED should be directly involved in screening the traffic data for accuracy and consistency as was done in this study.* The direct involvement of the TED in the screening of the traffic data significantly contributed to the accuracy of the

data and greatly contributed to the confidence the researchers place on the data used in the study.

5. *The Virginia Transportation Research Council (VTRC) should conduct a study as soon as feasible to verify whether incorporating independent variables for which data are available other than AADT, such as intersection geometry and other characteristics, will result in SPFs that better fit the Virginia data.* Although the currently suggested SafetyAnalyst SPFs use only the AADTs as the independent variables, it is likely that provision will be made for use of SPFs that incorporate other independent variables such as number of approaches, entering lanes and the other variables for which data are available, as these SPFs are likely to give better fit to crash data.

6. *As soon as feasible, VTRC should undertake a study to develop SPFs for the urban system intersections which are not currently maintained by VDOT, as these intersections may have different crash characteristics than those maintained by VDOT.* This would facilitate the use of SafetyAnalyst in programming sites that are currently not being maintained by VDOT.

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 that these SPFs do not fit the Virginia data very well. The results also indicate that the Virginia-specific SPFs 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 procedure given in SafetyAnalyst for prioritizing sites for safety improvements. This study has also shown that the EB method better identifies sites with higher potential for crash reduction than those identified by crash rates. For example, the illustrated examples given for the Bristol and Northern Virginia districts show that the potential reduction in FI crashes when the top 25 sites are identified by the EB method is 289.36 (14.96 + 274.40) crashes per year whereas that obtained when the critical crash ratio method is used for prioritization is only 19.63 (6.46 + 13.17) and that obtained with the crash rate method is only 6.90 (4.32 + 2.58) crashes per year. This gives a net benefit of 269.73 potential crashes per year compared to the critical crash ratio method and 282.46 compared to the crash rate method. Assuming an average cost of FI crashes of $95,629 (FHWA, 2005) and only 10% of the estimated net benefit PSI of 282.46 crashes per year is achieved, the total savings of more than $2.7 million per year could be accrued.

The prospects for implementation of the recommendations are very high as the study was requested by VDOT's TED, which is planning to incorporate these SPFs in the use of the tools provided in SafetyAnalyst.

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APPENDIX A

STATISTICAL PARAMETERS AND GOODNESS-OF-FIT RESULTS

Table A-1: Statistical Parameters for Urban Intersections SPFs

Data		**Parameter Estimates**								
		Intercept			**Coefficient of Mayor AADT**			**Coefficient of Minor AADT**		
Subtype	**Site**	**Intercept (α)**	***Stnd Error**	**P value**	**lnMajor (β1)**	***Stnd Error**	**P value**	**lnMinor (β2)**	***Stnd Error**	**P value**
Urban 4-Leg Signalized	**Total VA**	-7.6234	0.48	<.0001	0.6742	0.05	<.0001	0.3453	0.03	<.0001
	OR1	-8.3067	0.56	<.0001	0.7522	0.05	<.0001	0.328	0.03	<.0001
	OR10	-12.3913	1.22	<.0001	1.0631	0.13	<.0001	0.4567	0.06	<.0001
	OR 100	-8.8553	0.77	<.0001	0.7825	0.07	<.0001	0.3706	0.04	<.0001
	FI VA	-8.5256	0.57	<.0001	0.6477	0.06	<.0001	0.3579	0.04	<.0001
	OR1	-9.6546	0.63	<.0001	0.7603	0.06	<.0001	0.3597	0.04	<.0001
	OR10	-11.4284	1.5	<.0001	0.8662	0.16	<.0001	0.4412		
	OR 100	-9.9582	1.00	<.0001	0.7484	0.09	<.0001	0.4017	0.05	<.0001
Urban 4-Leg Minor Stop Control	**Total VA**	-6.0723	0.22	<.0001	0.4558	0.02	<.0001	0.347	0.04	<.0001
	OR1	-6.059	0.44	<.0001	0.505	0.04	<.0001	0.2773	0.06	<.0001
	OR10	-6.7031	0.57	<.0001	0.3986	0.07	<.0001	0.4999	0.09	<.0001
	OR 100	-6.5388	0.32	<.0001	0.4689	0.04	<.0001	0.43	0.06	<.0001
	FI VA	-7.6917	0.32	<.0001	0.5001	0.03	<.0001	0.3695	0.05	<.0001
	OR1	-8.1437	0.60	<.0001	0.5813	0.05	<.0001	0.3188	0.08	<.0001
	OR10	-8.0333	0.63	<.0001	0.3446	0.07	<.0001	0.6218	0.10	<.0001
	OR 100	-8.3166	0.51	<.0001	0.5253	0.06	<.0001	0.4695	0.08	<.0001
Urban 3-Leg Signalized	**Total VA**	-6.543	0.82	<.0001	0.6591	0.08	<.0001	0.2119	0.02	<.0001
	OR1	-4.999	1.03	<.0001	0.5555	0.09	<.0001	0.1554	0.03	<.0001
	OR10	-9.6143	1.27	<.0001	0.8677	0.12	<.0001	0.3297	0.05	<.0001
	OR 100	-6.7518	1.10	<.0001	0.6157	0.11	<.0001	0.2969	0.05	<.0001
	FI VA	-8.4268	0.68	<.0001	0.7147	0.06	<.0001	0.2481	0.02	<.0001
	OR1	-7.3982	0.99	<.0001	0.6496	0.09	<.0001	0.2088	0.03	<.0001
	OR10	-11.0104	1.55	<.0001	0.908	0.15	<.0001	0.3226	0.06	<.0001
	OR 100	-7.266	1.07	<.0001	0.5508	0.11	<.0001	0.3107	0.06	<.0001
Urban 3-Leg Minor Stop Control	**Total VA**	-5.4696	0.13	<.0001	0.4874	0.02	<.0001	0.1985	0.01	<.0001
	OR1	-5.361	0.18	<.0001	0.4959	0.02	<.0001	0.1676	0.02	<.0001
	OR10	-5.773	0.34	<.0001	0.4877	0.03	<.0001	0.2314	0.04	<.0001
	OR 100	-5.1642	0.21	<.0001	0.4338	0.03	<.0001	0.2309	0.03	<.0001
	FI VA	-7.4642	0.18	<.0001	0.5791	0.02	<.0001	0.2091	0.02	<.0001
	OR1	-7.6877	0.27	<.0001	0.6204	0.03	<.0001	0.181	0.02	<.0001
	OR10	-6.9458	0.47	<.0001	0.5096	0.04	<.0001	0.2212	0.05	<.0001
	OR 100	-6.9883	0.31	<.0001	0.5169	0.04	<.0001	0.2308	0.03	<.0001

*** Standard Error**

Table A-2: Statistical Parameters for Rural Intersections SPFs

Data		**Parameter Estimates**								
		Intercept			**Coefficient of Mayor AADT**			**Coefficient of Minor AADT**		
Subtype	**Site**	**Intercept (α)**	***Stnd Error**	**P value**	**lnMajor (β1)**	***Stnd Error**	**P value**	**lnMinor (β2)**	***Stnd Error**	**P value**
Rural 4-Leg Signalized	**Total VA**	-6.9589	1.18	**<.0001**	0.6746	0.09	**<.0001**	0.253	0.09	**0.0047**
	OR1	-1.604	2.37	**0.4974**	0.2284	0.21	**0.2791**	0.1514	0.12	**0.211**
	OR10	-6.3951	1.83	**0.0005**	0.5508	0.14	**0.0001**	0.3106	0.14	**0.0224**
	OR 100	-0.6468	2.20	**0.7692**	0.2262	0.16	**0.1635**	-0.0158	0.17	**0.9274**
	FI VA	-8.7116	1.28	**<.0001**	0.7839	0.11	**<.0001**	0.2166	0.09	**0.013**
	OR1	-3.3285	2.46	**0.1767**	0.3601	0.24	**0.126**	0.0597	0.13	**0.6478**
	OR10	-8.0583	1.75	**<.0001**	0.6809	0.18	**0.0001**	0.2557	0.13	**0.057**
	OR 100	-4.8381	2.21	**0.0287**	0.4243	0.18	**0.0193**	0.1523	0.18	**0.3943**
Rural 4-Leg Minor Stop Control	**Total VA**	-5.494	0.20	**<.0001**	0.3533	0.02	**<.0001**	0.3935	0.03	**<.0001**
	OR1	-6.2351	0.58	**<.0001**	0.4167	0.06	**<.0001**	0.4507	0.08	**<.0001**
	OR10	-5.3594	0.28	**<.0001**	0.3379	0.03	**<.0001**	0.3998	0.04	**<.0001**
	OR 100	-5.1255	0.27	**<.0001**	0.2914	0.03	**<.0001**	0.4075	0.04	**<.0001**
	FI VA	-6.6927	0.30	**<.0001**	0.3899	0.03	**<.0001**	0.4156	0.04	**<.0001**
	OR1	-8.2561	0.95	**<.0001**	0.5221	0.09	**<.0001**	0.4962	0.12	**<.0001**
	OR10	-7.0797	0.44	**<.0001**	0.3789	0.04	**<.0001**	0.497	0.05	**<.0001**
	OR 100	-6.3326	0.38	**<.0001**	0.3223	0.04	**<.0001**	0.4424	0.05	**<.0001**
Rural 3-Leg Signalized	**Total VA**	-7.5754	0.84	**<.0001**	0.6465	0.08	**<.0001**	0.3332	0.08	**<.0001**
	OR1	-5.8798	2.20	**0.0075**	0.5076	0.20	**0.0143**	0.313	0.13	**0.0161**
	OR10	-6.4368	1.10	**<.0001**	0.544	0.11	**<.0001**	0.2863	0.06	**<.0001**
	OR 100	-9.899	1.39	**<.0001**	0.8047	0.15	**<.0001**	0.4386	0.06	**<.0001**
	FI VA	-8.7112	1.03	**<.0001**	0.7224	0.10	**<.0001**	0.2578	0.06	**<.0001**
	OR1	-9.219	2.60	**0.0004**	0.7258	0.22	**0.0011**	0.3407	0.16	**0.0326**
	OR10	-8.8607	1.46	**<.0001**	0.7059	0.16	**<.0001**	0.2809	0.08	**0.0009**
	OR 100	-11.1835	1.85	**<.0001**	0.8669	0.18	**<.0001**	0.3977	0.08	**<.0001**
Rural 3-Leg Minor Stop Control	**Total VA**	-4.3293	0.08	**<.0001**	0.3366	0.01	**<.0001**	0.2087	0.01	**<.0001**
	OR1	-5.0904	0.22	**<.0001**	0.406	0.02	**<.0001**	0.2752	0.03	**<.0001**
	OR10	-4.0969	0.09	**<.0001**	0.3133	0.01	**<.0001**	0.2001	0.01	**<.0001**
	OR 100	-4.231	0.16	**<.0001**	0.2997	0.02	**<.0001**	0.2308	0.03	**<.0001**
	FI VA	-5.3415	0.11	**<.0001**	0.3394	0.01	**<.0001**	0.2237	0.01	**<.0001**
	OR1	-6.4457	0.31	**<.0001**	0.4195	0.03	**<.0001**	0.307	0.04	**<.0001**
	OR10	-5.0831	0.14	**<.0001**	0.3245	0.02	**<.0001**	0.2014	0.02	**<.0001**
	OR 100	-5.1046	0.24	**<.0001**	0.3163	0.03	**<.0001**	0.2112	0.03	**<.0001**

* Standard Error

Table A-3: SPFs Goodness of Fit Results for Urban Northern Operational Region (No. 1)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Urban 4-Leg Signalized	Total VA	41.150	0.529	0.557	-0.760	4.329	38.490	0.575
	Total R1	41.10	0.51	0.551	-0.20	4.64	44.86	0.54
	FI VA	7.04	0.38	0.406	-0.46	1.94	7.67	0.48
	FI R1	8.09	0.39	0.439	0.12	2.14	9.50	0.38
Urban 4-Leg Minor Stop Control	Total VA	2.24	0.31	0.313	-0.03	0.90	2.38	0.29
	Total R1	3.08	0.28	0.286	0.08	0.95	2.00	0.32
	FI VA	0.53	0.19	0.193	0.00	0.43	0.53	0.19
	FI R1	0.64	0.18	0.187	0.03	0.43	0.48	0.21
Urban 3-Leg Signalized	Total VA	24.90	0.38	0.370	-0.64	3.52	27.59	0.37
	Total R1	30.34	0.32	0.305	-0.15	3.65	26.87	0.37
	FI VA	4.47	0.28	0.259	-0.19	1.53	4.88	0.26
	FI R1	5.59	0.25	0.231	0.04	1.57	4.48	0.29
Urban 3-Leg Minor Stop Control	Total VA	1.85	0.25	0.230	-0.04	0.89	2.04	0.24
	Total R1	2.08	0.26	0.239	-0.06	0.94	2.19	0.26
	FI VA	0.43	0.15	0.133	-0.02	0.43	0.48	0.16
	FI R1	0.47	0.17	0.156	-0.01	0.44	0.50	0.17

Table A-4: SPFs Goodness of Fit Results for Urban Western Operational Region (No. 10)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Urban 4-Leg Signalized	Total VA	41.150	0.529	0.557	-0.760	4.329	38.490	0.575
	Total R10	21.976	0.777	0.735	1.290	3.233	17.910	0.686
	FI VA	7.043	0.385	0.406	-0.458	1.938	7.671	0.475
	FI R10	4.280	0.526	0.500	0.377	1.597	5.170	0.452
Urban 4-Leg Minor Stop Control	Total VA	2.238	0.315	0.313	-0.034	0.897	2.383	0.292
	Total R10	1.161	0.361	0.300	-0.032	0.740	1.050	0.188
	FI VA	0.530	0.194	0.193	-0.004	0.432	0.533	0.194
	FI R10	0.312	0.197	0.187	0.000	0.382	0.330	0.009
Urban 3-Leg Signalized	Total VA	24.900	0.375	0.370	-0.645	3.519	27.591	0.369
	Total R10	14.446	0.451	0.397	-0.168	2.801	24.410	0.255
	FI VA	4.467	0.275	0.259	-0.185	1.527	4.875	0.262
	FI R10	3.077	0.266	0.216	0.039	1.258	3.390	0.115
Urban 3-Leg Minor Stop Control	Total VA	1.854	0.254	0.230	-0.043	0.893	2.038	0.239
	Total R10	1.391	0.233	0.197	-0.054	0.800	1.640	0.207
	FI VA	0.428	0.151	0.133	-0.021	0.431	0.476	0.157
	FI R10	0.354	0.111	0.089	-0.019	0.404	0.380	0.125

Table A-5: SPFs Goodness of Fit Results for Urban Eastern Operational Region (No. 100)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Urban 4-Leg Signalized	Total VA	41.150	0.529	0.557	-0.760	4.329	38.490	0.575
	Total R100	31.108	0.632	0.630	0.243	4.717	37.450	0.005
	FI VA	7.043	0.385	0.406	-0.458	1.938	7.671	0.475
	FI R100	5.201	0.480	0.454	-0.098	1.864	5.410	0.244
Urban 4-Leg Minor Stop Control	Total VA	2.238	0.315	0.313	-0.034	0.897	2.383	0.292
	Total R100	1.720	0.443	0.381	0.087	0.758	1.150	0.003
	FI VA	0.530	0.194	0.193	-0.004	0.432	0.533	0.194
	FI R100	0.509	0.273	0.254	0.049	0.383	0.360	0.173
Urban 3-Leg Signalized	Total VA	24.900	0.375	0.370	-0.645	3.519	27.591	0.369
	Total R100	17.782	0.410	0.410	-1.753	0.908	38.780	0.004
	FI VA	4.467	0.275	0.259	-0.185	1.527	4.875	0.262
	FI R100	3.194	0.243	0.263	-0.615	1.645	5.860	0.236
Urban 3-Leg Minor Stop Control	Total VA	1.854	0.254	0.230	-0.043	0.893	2.038	0.239
	Total R100	1.561	0.233	0.210	-0.127	0.902	2.230	0.002
	FI VA	0.428	0.151	0.133	-0.021	0.431	0.476	0.157
	FI R100	0.387	0.131	0.116	-0.043	0.444	0.500	0.141

Table A-6: SPFs Goodness of Fit Results for Rural Northern Operational Region (No. 1)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Rural 4-Leg Signalized	Total VA	10.990	0.353	0.321	0.513	2.210	10.070	-0.073
	Total R1	20.080	0.118	0.092	-1.389	3.661	34.220	0.212
	FI VA	2.350	0.196	0.181	0.045	1.189	2.600	-0.034
	FI R1	2.920	0.057	0.052	-1.173	1.931	9.760	0.028
Rural 4-Leg Minor Stop Control	Total VA	1.090	0.182	0.167	-0.067	0.794	1.190	0.171
	Total R1	1.990	0.190	0.245	0.001	0.942	1.640	0.173
	FI VA	0.480	0.112	0.098	-0.022	0.504	0.530	0.110
	FI R1	0.920	0.093	0.112	0.020	0.541	0.520	0.009
Rural 3-Leg Signalized	Total VA	5.490	0.328	0.305	-0.010	1.651	5.760	0.179
	Total R1	11.110	0.182	0.254	-0.679	2.271	14.750	0.497
	FI VA	1.450	0.181	0.170	-0.041	0.902	1.710	0.099
	FI R1	3.230	0.131	0.153	-0.116	1.006	2.120	0.355
Rural 3-Leg Minor Stop Control	Total VA	0.690	0.144	0.104	-0.008	0.613	0.730	0.102
	Total R1	1.210	0.245	0.196	0.030	0.712	0.930	0.126
	FI VA	0.250	0.071	0.048	-0.009	0.345	0.260	0.048
	FI R1	0.340	0.124	0.093	0.016	0.366	0.300	0.052

Table A-7: SPFs Goodness of Fit Results for Rural Western Operational Region (No. 10)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	**Site**	**MSE**	**r^2**	**R^2_{FT}**	**MPB**	**MAD**	**MSPE**	**R^2_{FT}**
Rural 4-Leg Signalized	Total VA	10.990	0.353	0.321	0.513	2.210	10.070	-0.073
	Total R10	6.020	0.311	0.268	0.007	1.748	6.050	0.382
	FI VA	2.350	0.196	0.181	0.045	1.189	2.600	-0.034
	FI R10	1.880	0.158	0.139	0.097	0.945	1.590	0.254
Rural 4-Leg Minor Stop Control	Total VA	1.090	0.182	0.167	-0.067	0.794	1.190	0.171
	Total R10	1.300	0.196	0.163	0.070	0.760	1.020	0.078
	FI VA	0.480	0.112	0.098	-0.022	0.504	0.530	0.110
	FI R10	0.560	0.142	0.118	0.025	0.495	0.480	0.014
Rural 3-Leg Signalized	Total VA	5.490	0.328	0.305	-0.010	1.651	5.760	0.179
	Total R10	3.690	0.163	0.170	-0.432	0.748	6.740	0.039
	FI VA	1.450	0.181	0.170	-0.041	0.902	1.710	0.099
	FI R10	0.890	0.124	0.117	-0.391	0.997	4.030	-0.066
Rural 3-Leg Minor Stop Control	Total VA	0.690	0.144	0.104	-0.008	0.613	0.730	0.102
	Total R10	0.640	0.126	0.091	0.025	0.583	0.580	0.055
	FI VA	0.250	0.071	0.048	-0.009	0.345	0.260	0.048
	FI R10	0.240	0.062	0.041	0.003	0.335	0.230	0.028

Table A-8: SPFs Goodness of Fit Results for Rural Eastern Operational Region (No. 100)

Data		Estimation Data 70%			Validation Data 30%			
Subtype	Site	MSE	r^2	R^2_{FT}	MPB	MAD	MSPE	R^2_{FT}
Rural 4-Leg Signalized	Total VA	10.990	0.353	0.321	0.513	2.210	10.070	-0.073
	Total R100	10.120	0.042	0.027	1.207	1.882	5.120	-0.307
	FI VA	2.350	0.196	0.181	0.045	1.189	2.600	-0.034
	FI R100	2.060	0.053	0.039	0.119	0.962	1.370	-0.023
Rural 4-Leg Minor Stop Control	Total VA	1.090	0.182	0.167	-0.067	0.794	1.190	0.171
	Total R100	0.960	0.170	0.149	-0.086	0.746	1.140	0.209
	FI VA	0.480	0.112	0.098	-0.022	0.504	0.530	0.110
	FI R100	0.440	0.106	0.092	-0.031	0.475	0.490	0.121
Rural 3-Leg Signalized	Total VA	5.490	0.328	0.305	-0.010	1.651	5.760	0.179
	Total R100	2.770	0.492	0.459	0.601	1.759	6.260	0.090
	FI VA	1.450	0.181	0.170	-0.041	0.902	1.710	0.099
	FI R100	1.040	0.265	0.255	0.124	0.923	1.570	-0.055
Rural 3-Leg Minor Stop Control	Total VA	0.690	0.144	0.104	-0.008	0.613	0.730	0.102
	Total R100	0.640	0.125	0.087	-0.037	0.601	0.690	0.119
	FI VA	0.250	0.071	0.048	-0.009	0.345	0.260	0.048
	FI R100	0.250	0.064	0.038	-0.013	0.345	0.270	0.062

APPENDIX B

RECOMMENDED SAFETY PERFORMANCE FUNCTION MODELS

Table B-1: Recommended Urban SPFs

Site		Virginia SPF Models to Be Used for Urban Intersections	
Urban 4-Leg Signalized	**Total Virginia**	generic total	$e^{-7.6234} \times MajADT^{0.6748} \times MinADT^{0.3423}$
Urban 4-Leg Signalized	Operational Region 1	generic total	$e^{-7.6234} \times MajADT^{0.6748} \times MinADT^{0.3423}$
Urban 4-Leg Signalized	Operational Region 10	use specified model developed	$e^{-15.3143} \times MajADT^{1.0681} \times MinADT^{0.4167}$
Urban 4-Leg Signalized	Operational Region 100	generic total	$e^{-7.6234} \times MajADT^{0.6748} \times MinADT^{0.3423}$
Urban 4-Leg Signalized	**FI Virginia**	generic FI	$e^{-8.3258} \times MajADT^{0.6477} \times MinADT^{0.3379}$
Urban 4-Leg Signalized	Operational Region 1	generic FI	$e^{-8.3258} \times MajADT^{0.6477} \times MinADT^{0.3379}$
Urban 4-Leg Signalized	Operational Region 10	use specified model developed	$e^{-44.4284} \times MajADT^{0.8662} \times MinADT^{0.4418}$
Urban 4-Leg Signalized	Operational Region 100	use specified model developed	$e^{-9.9885} \times MajADT^{0.7484} \times MinADT^{0.4017}$
Urban 4-Leg Minor Stop Control	**Total Virginia**	generic total	$e^{-6.0793} \times MajADT^{0.4358} \times MinADT^{0.3470}$
Urban 4-Leg Minor Stop Control	Operational Region 1	use specified model developed	$e^{-6.0590} \times MajADT^{0.5080} \times MinADT^{0.2578}$
Urban 4-Leg Minor Stop Control	Operational Region 10	use specified model developed	$e^{-6.7061} \times MajADT^{0.2986} \times MinADT^{0.4999}$
Urban 4-Leg Minor Stop Control	Operational Region 100	use specified model developed	$e^{-6.3388} \times MajADT^{0.4689} \times MinADT^{0.4300}$
Urban 4-Leg Minor Stop Control	**FI Virginia**	generic FI	e^-7.6917*MajADT^0.5001*MinADT^0.3695
Urban 4-Leg Minor Stop Control	Operational Region 1	use specified model developed	$e^{-8.4457} \times MajADT^{0.5818} \times MinADT^{0.3188}$
Urban 4-Leg Minor Stop Control	Operational Region 10	use specified model developed	$e^{-9.0333} \times MajADT^{0.5446} \times MinADT^{0.6818}$
Urban 4-Leg Minor Stop Control	Operational Region 100	use specified model developed	$e^{-8.8166} \times MajADT^{0.5825} \times MinADT^{0.4695}$

Table B-1: Recommended Urban SPFs (Continued)

Site		Virginia SPF Models to Be Used for Urban Intersections	
Urban 3-Leg Signalized	**Total Virginia**	use generic model developed for total crashes	$e^{-6.5430} \times MajADT^{0.6891} \times MinADT^{0.2119}$
Urban 3-Leg Signalized	Operational Region 1	use generic model developed for total crashes	$e^{-6.5430} \times MajADT^{0.6891} \times MinADT^{0.2119}$
Urban 3-Leg Signalized	Operational Region 10	use specific regional model developed	$e^{-9.6443} \times MajADT^{0.8677} \times MinADT^{0.2287}$
Urban 3-Leg Signalized	Operational Region 100	use generic model developed for total crashes	$e^{-6.5430} \times MajADT^{0.6891} \times MinADT^{0.2119}$
Urban 3-Leg Signalized	**FI Virginia**	use generic model developed for FI crashes	$e^{-8.4538} \times MajADT^{0.7147} \times MinADT^{0.2481}$
Urban 3-Leg Signalized	Operational Region 1	use generic model developed for FI crashes	$e^{-8.4538} \times MajADT^{0.7147} \times MinADT^{0.2481}$
Urban 3-Leg Signalized	Operational Region 10	use specific regional model developed	$e^{-11.0404} \times MajADT^{0.9089} \times MinADT^{0.2286}$
Urban 3-Leg Signalized	Operational Region 100	use generic model developed for FI crashes	$e^{-8.4538} \times MajADT^{0.7147} \times MinADT^{0.2481}$
Urban 3-Leg Minor Stop Control	**Total Virginia**	use generic model developed for total crashes	$e^{-3.4696} \times MajADT^{0.4874} \times MinADT^{0.1988}$
Urban 3-Leg Minor Stop Control	Operational Region 1	use generic model developed for total crashes	$e^{-3.4696} \times MajADT^{0.4874} \times MinADT^{0.1988}$
Urban 3-Leg Minor Stop Control	Operational Region 10	use specific regional model developed	$e^{-3.7739} \times MajADT^{0.4857} \times MinADT^{0.2214}$
Urban 3-Leg Minor Stop Control	Operational Region 100	use generic model developed for total crashes	$e^{-3.4696} \times MajADT^{0.4874} \times MinADT^{0.1988}$
Urban 3-Leg Minor Stop Control	**FI Virginia**	use generic model developed for FI crashes	$e^{-7.4645} \times MajADT^{0.5771} \times MinADT^{0.2091}$
Urban 3-Leg Minor Stop Control	Operational Region 1	use generic model developed for FI crashes	$e^{-7.4645} \times MajADT^{0.5771} \times MinADT^{0.2091}$
Urban 3-Leg Minor Stop Control	Operational Region 10	use specific regional model developed	$e^{-6.9438} \times MajADT^{0.5096} \times MinADT^{0.2216}$
Urban 3-Leg Minor Stop Control	Operational Region 100	use generic model developed for FI crashes	$e^{-7.4645} \times MajADT^{0.5771} \times MinADT^{0.2091}$

Table B-2: Recommended Rural SPFs

Site		Virginia SPF Models to Be Used for Rural Intersections	
Rural 4-Leg Signalized	**Total Virginia**	use generic model developed for total crashes	$e^{-6.86} \times MajADT^{0.67} \times MinADT^{0.43}$
Rural 4-Leg Signalized	Operational Region 1	use generic model developed for total crashes	$e^{-1.60} \times MajADT^{0.63} \times MinADT^{0.43}$
Rural 4-Leg Signalized	Operational Region 10	use specific regional model developed	$e^{-6.40} \times MajADT^{0.33} \times MinADT^{0.31}$
Rural 4-Leg Signalized	Operational Region 100	use specific regional model developed	$e^{-0.63} \times MajADT^{0.63} \times MinADT^{0.06}$
Rural 4-Leg Signalized	**FI Virginia**	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.78} \times MinADT^{0.66}$
Rural 4-Leg Signalized	Operational Region 1	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.78} \times MinADT^{0.66}$
Rural 4-Leg Signalized	Operational Region 10	use specific regional model developed	$e^{-8.06} \times MajADT^{0.68} \times MinADT^{0.56}$
Rural 4-Leg Signalized	Operational Region 100	use specific regional model developed	$e^{-4.84} \times MajADT^{0.42} \times MinADT^{0.43}$
Rural 4-Leg Minor Stop Control	**Total Virginia**	use generic model developed for total crashes	$e^{-5.49} \times MajADT^{0.35} \times MinADT^{0.39}$
Rural 4-Leg Minor Stop Control	Operational Region 1	use generic model developed for total crashes	e^-5.49*MajADT^0.35*MinADT^0.39
Rural 4-Leg Minor Stop Control	Operational Region 10	use specific regional model developed	$e^{-5.36} \times MajADT^{0.34} \times MinADT^{0.40}$
Rural 4-Leg Minor Stop Control	Operational Region 100	use generic model developed for total crashes	$e^{-5.49} \times MajADT^{0.35} \times MinADT^{0.39}$
Rural 4-Leg Minor Stop Control	**FI Virginia**	use generic model developed for FI crashes	$e^{-6.69} \times MajADT^{0.39} \times MinADT^{0.45}$
Rural 4-Leg Minor Stop Control	Operational Region 1	use generic model developed for FI crashes	$e^{-6.69} \times MajADT^{0.39} \times MinADT^{0.45}$
Rural 4-Leg Minor Stop Control	Operational Region 10	use generic model developed for FI crashes	$e^{-6.69} \times MajADT^{0.39} \times MinADT^{0.45}$
Rural 4-Leg Minor Stop Control	Operational Region 100	use generic model developed for FI crashes	$e^{-6.69} \times MajADT^{0.39} \times MinADT^{0.45}$

Table B-2: Recommended Rural SPFs (Continued)

Site		Virginia SPF Models to Be Used for Rural Intersections	
Rural 3-Leg Signalized	**Total Virginia**	use generic model developed for total crashes	$e^{-7.88} \times MajADT^{0.68} \times MinADT^{0.33}$
Rural 3-Leg Signalized	Operational Region 1	use generic model developed for total crashes	$e^{-7.88} \times MajADT^{0.68} \times MinADT^{0.33}$
Rural 3-Leg Signalized	Operational Region 10	use generic model developed for total crashes	$e^{-7.88} \times MajADT^{0.68} \times MinADT^{0.33}$
Rural 3-Leg Signalized	Operational Region 100	use generic model developed for total crashes	$e^{-7.88} \times MajADT^{0.68} \times MinADT^{0.33}$
Rural 3-Leg Signalized	**FI Virginia**	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.75} \times MinADT^{0.26}$
Rural 3-Leg Signalized	Operational Region 1	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.75} \times MinADT^{0.26}$
Rural 3-Leg Signalized	Operational Region 10	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.75} \times MinADT^{0.26}$
Rural 3-Leg Signalized	Operational Region 100	use generic model developed for FI crashes	$e^{-8.71} \times MajADT^{0.75} \times MinADT^{0.26}$
Rural 3-Leg Minor Stop Control	**Total Virginia**	use generic model developed for total crashes	$e^{-4.33} \times MajADT^{0.54} \times MinADT^{0.41}$
Rural 3-Leg Minor Stop Control	Operational Region 1	use generic model developed for total crashes	$e^{-4.33} \times MajADT^{0.54} \times MinADT^{0.41}$
Rural 3-Leg Minor Stop Control	Operational Region 10	use specific regional model developed	$e^{-4.10} \times MajADT^{0.51} \times MinADT^{0.20}$
Rural 3-Leg Minor Stop Control	Operational Region 100	use generic model developed for total crashes	$e^{-4.33} \times MajADT^{0.54} \times MinADT^{0.41}$
Rural 3-Leg Minor Stop Control	**FI Virginia**	use generic model developed for FI crashes	$e^{-5.84} \times MajADT^{0.54} \times MinADT^{0.22}$
Rural 3-Leg Minor Stop Control	Operational Region 1	use generic model developed for FI crashes	$e^{-5.84} \times MajADT^{0.54} \times MinADT^{0.22}$
Rural 3-Leg Minor Stop Control	Operational Region 10	use specific regional model developed	$e^{-5.08} \times MajADT^{0.56} \times MinADT^{0.20}$
Rural 3-Leg Minor Stop Control	Operational Region 100	use generic model developed for FI crashes	$e^{-5.84} \times MajADT^{0.54} \times MinADT^{0.22}$