

Safety Performance Function Decision Guide: SPF Calibration versus SPF Development

Final Report

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Contents

- Acknowledgements 5
- Executive Summary 6
- 1. Background and Context..... 7
 - Organization of this Document 7
- 2. What Are SPFs? 8
- 3. How Are SPFs Used? 9
 - Network Screening Level: Identifying Locations with Promise 9
 - Project Level: Determining the Expected Safety Impacts of Design Changes..... 9
 - Evaluating the Effect of Engineering Treatments..... 9
- 4. Options for Obtaining SPFs for a Jurisdiction..... 11
 - Calibrating SPFs 11
 - Developing SPFs 14
- 5. Decision Process: How an Agency Obtains SPFs 17
 - Step-by-Step Process 17
 - Staff Time Required for Calibration and Development 20
- References 22
- Appendix A: Roadway and Intersection Types for which SPFs are provided in the HSM (1st Edition) and *Safety Analyst*..... 24
- Appendix B. Developing an Intersection Inventory..... 26
- Appendix C. Recent SPF Development Efforts from States 28

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Executive Summary

This guidebook is intended to provide guidance on whether an agency should calibrate the safety performance functions (SPFs) from the Highway Safety Manual (HSM) or develop jurisdiction-specific SPFs. The guidebook discusses the factors that need to be considered while making the decision. It is intended to be of use to practitioners at state and local agencies and to researchers.

The guidebook starts with a brief overview of other documents being developed by FHWA and NCHRP to facilitate the implementation of the HSM. This is followed by a brief discussion of “What are SPFs” (Section 2). This is then followed by a brief discussion on how SPFs are used for different applications, i.e., network screening, project level analysis, and determining the safety effect of improvements (Section 3).

Section 4 is a discussion of the options for obtaining SPFs for a jurisdiction. The two options: (1) calibration of existing SPFs, and (2) development of jurisdiction specific SPFs, are discussed along with a brief overview of the steps involved in the calibration and development of jurisdiction specific SPFs.

Section 5 discusses the step by step process that an agency could use to obtain SPFs. The following steps are discussed:

- Step 1. Determine intended use of SPF
- Step 2. Determine facility type
- Step 3. Identify existing SPF
- Step 4. Consider sample size necessary for calibrating SPF
- Step 5. Consider roadway data necessary for calibrating SPF
- Step 6. Calibrate existing SPF
- Step 7. Assess quality of calibration factor
- Step 8. Consider statistical expertise necessary for developing SPF
- Step 9. Consider sample size necessary for developing SPF
- Step 10. Determine crash type to be addressed by SPF
- Step 11. Develop SPF

Section 5 also discusses the staff required for calibration and development of jurisdiction-specific SPFs. The staff time estimates are based on the judgment of the project team.

This report also includes three appendices. Appendix A provides the list of intersection and roadway types for which SPFs are available in the first edition of the HSM and *Safety Analyst*. Appendix B is a discussion of the major considerations in building an intersection inventory. Appendix C is a brief description of recent jurisdiction-specific SPF development efforts from different States.

1. Background and Context

This guidebook is intended to provide guidance on whether an agency should calibrate the safety performance functions (SPFs) from the Highway Safety Manual (HSM) (AASHTO, 2010) or develop jurisdiction-specific SPFs. The guidebook discusses the factors that need to be considered while making the decision. It is intended to be of use to practitioners at state and local agencies and to researchers.

This document is part of a series of documents currently being developed by the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP) to facilitate the implementation of the HSM by the States. Following is the list of the other documents being prepared as part of the series:

- NCHRP Project 20-7 (Task 332): This effort, led by Dr. Geni Bahar of NAVIGATS will develop a *User's Guide to Develop Highway Safety Manual Safety Performance Function Calibration Factors* (hereafter referred to as the **SPF Calibration Guide**). This document will provide guidelines to assist an agency in developing statistically sound calibration factors. This document will also provide guidance for assessing the quality of a calibration factor after it is developed.
- *Safety Performance Function Development Guide: Developing Jurisdiction Specific SPFs* (hereafter referred to as the **SPF Development Guide**). If a jurisdiction decides that developing jurisdiction-specific SPFs will fit their needs, this document will provide knowledge of what data, expertise, tools, and other resources are required to develop jurisdiction-specific SPFs. This effort is currently being funded by FHWA.
- *SPF Needs Assessment*: This project, led by Volpe did a needs and alternatives assessment to determine the set of potential resources that would best satisfy the future needs of the states using SPFs. Part of this project involved conducting interviews with selected States to better understand their needs and requirements regarding SPFs. Further information about this effort can be obtained from <http://safety.fhwa.dot.gov/rsdp/>.

Organization of this Document

The next section of this document gives a brief discussion of “What are SPFs” (Section 2). This is then followed by a brief discussion on how SPFs are used for different applications, i.e., network screening, project level analysis, and determining the safety effect of improvements (Section 3). Section 4 is a discussion of the options for obtaining SPFs for a jurisdiction. Section 5 discusses the step by step process that an agency could use to obtain SPFs. This is followed by a list of references. The document concludes with three Appendices.

2. What Are SPFs?

SPFs are crash prediction models. They are essentially mathematical equations that relate the number of crashes of different types to site characteristics. These models always include traffic volume (AADT) but may also include site characteristics such as lane width, shoulder width, radius/degree of horizontal curves, presence of turn lanes (at intersections), and traffic control (at intersections). One example is the following SPF from *Safety Analyst* for predicting the total number of crashes on rural multilane divided roads:

$$P = L \times e^{-5.05} \times (AADT)^{0.66}$$

Where:

P is the total number of crashes in 1 year on a segment of length L.

The primary purpose of this SPF from *Safety Analyst*¹ is to assist an agency in their network screening process, i.e., to identify sites that may benefit from a safety treatment. This is a relatively simple SPF where the predicted number of crashes per mile is a function of just AADT. On the other hand, Bauer and Harwood (2012) provide a more complex prediction model for fatal and injury crashes on rural two lane roads:

$$N_{FI} = \exp \left[b_0 + b_1 \ln(AADT) + b_2 G + b_3 \ln \left(2 \times \frac{5730}{R} \right) \times I_{HC} + b_4 \left(\frac{1}{R} \right) \left(\frac{1}{L_C} \right) \times I_{HC} \right]$$

Where:

N_{FI}	=	fatal-and-injury crashes/mi/yr
AADT	=	veh/day
G	=	absolute value of percent grade; 0 percent for level tangents; ≥ 1 percent otherwise
R	=	curve radius (ft); missing for tangents
I_{HC}	=	horizontal curve indicator: 1 for horizontal curves; 0 otherwise
L_C	=	horizontal curve length (mi); not applicable for tangents
ln	=	natural logarithm function
b_0, \dots, b_4	=	regression coefficients

This prediction model was estimated using data from Washington. This model was estimated to examine the safety aspects of horizontal and vertical curvature.

¹ Safety Analyst is a set of software tools that can be used by state and local agencies for highway safety management. It is available for licensing as an AASHTOWare product (see www.safetyanalyst.org for further details).

3. How Are SPFs Used?

The HSM outlines at least three different ways in which SPFs can be used by jurisdictions to make better safety decisions. One application is to use SPFs as part of network screening to identify sections that may have the best potential for improvements (i.e., Part B of the HSM). The second application is to use SPFs to determine the safety impacts of design changes at the project level (i.e., Part C of the HSM). The third application is the use of SPFs as part of a before-after study to evaluate the safety effects of engineering treatments. Following is a brief discussion of these applications.

Network Screening Level: Identifying Locations with Promise

SPFs may be used to identify locations with promise, which are locations that may benefit the most from a safety treatment. This application is also referred to as network screening. Here, SPFs can be used to estimate the predicted number of crashes for a particular facility type with a particular traffic volume. This predicted number can then be compared to the observed number of crashes at a particular site to predict the expected number of crashes at that site. This result is used to determine if that site should be categorized as a “site with promise”. Methods for using SPFs in network screening are discussed in Part B of the HSM. SPFs that could be used for network screening are available in *Safety Analyst*, a set of software tools that can be used by state and local agencies for safety management. Appendix A of this document provides the default list of roadway, intersection, and ramp types for which SPFs are provided in *Safety Analyst*.

Project Level: Determining the Expected Safety Impacts of Design Changes

When SPFs are used in project-level decision making, they are used for estimating the *average expected crash frequency* for existing conditions, alternatives to existing conditions, or proposed new roadways. Part C of the HSM provides methods for estimating the average expected crash frequency of a site or project. These methods involve the use of SPFs for predicting the crash frequency for a “base” condition and crash modification factors (CMFs) to adjust the predictions for situations that differ from that base condition. The SPFs for these base conditions along with the CMFs are available in Part C of the HSM. The list of roadway and intersection types for which SPFs are available in Part C of the HSM is provided in Appendix A of this document.

Evaluating the Effect of Engineering Treatments

Researchers commonly conduct safety evaluation studies to determine the effect on crashes (e.g., CMF) from implementing some safety countermeasure. Most safety researchers agree that before-after studies provide more reliable estimates of the safety effect of engineering treatments than do cross-sectional comparisons of locations with and without a particular treatment. Since many engineering treatments are implemented at locations that may have a higher than normal crash count, before-after studies need to account for potential bias due to regression to the mean. One way to address this bias is

to make use of the empirical Bayes (EB) procedure developed by Hauer (1997). SPFs are an integral part of the EB procedure. This guide does not discuss the application of SPFs as part of before-after evaluations. Further discussion of this application can be found in Hauer (1997) and Gross et al. (2010).

For some situations where before-after evaluations are not feasible, the coefficients of the variables from SPFs can be used to estimate the CMF associated with a particular treatment. However, there are a number of issues associated with this approach for developing CMFs. This guide does not discuss the use of SPFs for this application. A detailed discussion of the issues associated with such applications of SPFs is provided Hauer (2010, 2013), Elvik (2011), and Carter et al. (2012).

4. Options for Obtaining SPFs for a Jurisdiction

An agency has two choices for obtaining SPFs to use in the above applications – calibrating existing SPFs or developing jurisdiction-specific SPFs (hereafter referred to as “calibrating SPFs” and “developing SPFs”, respectively). These options are described in the following sections.

Calibrating SPFs

One option for obtaining SPFs is to take existing SPFs that were developed in other geographic areas and calibrate them for the local jurisdiction. If an agency wants to make use of existing SPFs from sources such as the HSM or *Safety Analyst*, they need to be calibrated for the conditions in the jurisdiction. Calibration is necessary because “the general level of crash frequencies may vary substantially from one jurisdiction to another for a variety of reasons including crash reporting thresholds and crash reporting system procedures” (HSM, page C-18). This section provides an overview of calibration. Further discussion of the issues and steps will be available from the *SPF Calibration Guide* that is being developed under NCHRP Project 20-07 (Task 332).

Sources of Existing SPFs

Existing SPFs may be obtained from sources such as Part C of the Highway Safety Manual (for project level analysis) or *Safety Analyst* (for network screening). Regarding the SPFs in Part C of the HSM, Chapter 10 includes SPFs that were estimated for rural two-lane, two-way roads developed using state data from Minnesota, Washington, Michigan, and California. Chapter 11 includes SPFs that were estimated for rural multilane highways using data from Texas, California, Minnesota, New York, and Washington. Chapter 12 includes SPFs for roadway segments in urban and suburban arterials that were estimated using data from Minnesota, Michigan, and Washington; the SPFs for intersections in urban and suburban arterials were estimated using data from Minnesota, North Carolina, Florida, and Toronto (Ontario). It should be noted that before these SPFs were included in the HSM, the roadway segment SPFs were calibrated using data from Washington and the intersection SPFs were calibrated using data from California (Srinivasan et al., 2008).

Safety Analyst includes SPFs for roadway segments, intersections, and ramps. SPFs for roadway segments were estimated using data from Ohio, North Carolina, Minnesota, California, and Washington. SPFs for intersections were estimated using data from Minnesota, and SPFs for ramps were estimated using data from Washington. Calibration of these SPFs is automatically done within the software. Although the *Safety Analyst* program and technical support are only available through purchase from AASHTO, the default SPFs used in *Safety Analyst* are documented in Appendix E of Harwood et al., (2010).

The SPFs in Part C of the HSM and in *Safety Analyst* are negative binomial (NB) regression models estimated using a procedure called generalized linear models (GLM).

Calibration Process

As discussed earlier, SPFs are essentially mathematical equations that relate the number of crashes of different types to site characteristics. Mathematically speaking, an SPF can be represented in the following manner:

$$N_p = f(AADT, X_1, X_2, X_3, X_4, \dots)$$

Where N_p is the predicted number of crashes during a particular time as a function of traffic volume (AADT), and other site characteristics, X_1, X_2, X_3, X_4 , and so on (f is a mathematical function that relates the predicted number of crashes with AADT and other site characteristics). The relevant site characteristics (X_1, X_2, X_3, X_4 and so on) may also be different depending on the type of road and whether it is a roadway segment, intersection, or ramp. For example, in the case of intersections, AADT may be replaced by major road AADT and minor road AADT.

In the context of calibration, it is important to understand the distinction between the SPFs in *Safety Analyst* that are intended for network screening and the SPFs from Part C of the HSM that are intended for project level analysis.

- ***SPFs for network screening.*** The SPFs for roadway segments and ramps in *Safety Analyst* predict the number of crashes per mile per year and include AADT as the only independent variable. Similarly, the SPFs for intersections in *Safety Analyst* predict the number of crashes per intersection per year and include major and minor road AADT as the only independent variables. However, the SPFs in *Safety Analyst* were not estimated for any particular base condition. These SPFs are intended to provide the average number of crashes for a particular traffic volume level for a particular type of facility (the list of facility types covered in *Safety Analyst* is provided in Appendix A of this document).
- ***SPFs for project level analysis.*** As mentioned earlier, the prediction methods in Part C of the HSM involve the use of SPFs for predicting the crash frequency for a “base” condition and crash modification factors (CMFs) to adjust the predictions for situations that are different from a base condition. For roadway segments, the prediction methods provide estimates for the number of crashes per mile per year, and for intersections, the prediction methods for base conditions provide estimates for the number of crashes per intersection per year. Typically, the SPFs for base conditions include AADT (for roadway segments) as the independent variable, and major and minor road AADTs as independent variables for intersections. CMFs are then used to adjust this prediction for situations other than the base condition.

Below is a brief listing of the steps involved in calibrating network screening SPFs from *Safety Analyst* and project level SPFs from Part C of the HSM.

Steps in Calibrating Network Screening SPFs

The steps involved in calibrating network screening SPFs are similar to those when calibrating project-level SPFs since the ultimate aim is to determine the ratio of the total number of observed crashes to

the total number of predicted crashes. However, there are differences in the details of these steps since both the SPFs and the data requirements are different. Following is an outline of the steps:

- Step 1 – Identify facility types and appropriate SPFs. As discussed earlier, the SPFs in *Safety Analyst* are a logical starting point since SPFs are available for a large number of facility types and have already been used in the software. However, there is no reason why a jurisdiction could not make use of similar SPFs that were developed by other researchers, particularly if they had been estimated using data from the same jurisdiction from an earlier time period. In this context, it is important to note that *Safety Analyst* allows users to import custom SPFs and calibration is automatically done within the software before further analyses are conducted. Hence, the discussion of these steps are intended for those users who may want to use *Safety Analyst* type SPFs for network screening without actually using the software package.
- Step 2 – Select sites for calibration. Unlike project level analysis where individual sites or group of sites are examined one at a time, network screening makes use of data from the entire network (for a particular facility type). Hence, the sample for calibration needs to cover the network that needs to be screened. Again, depending on the variation in terrain, climate, topography, crash reporting practices, driver population, animal population, and other factors across the jurisdiction, multiple calibration factors may be necessary if the jurisdiction feels that screening should be done separately for different groups based on these factors. *Safety Analyst* allows the user to create regional site sub-types that can be calibrated with regional data.
- Step 3 – Obtain data for each facility type. Apart from crash counts, data for calibrating network screening SPFs could simply include AADT and segment length (for roadway segments and ramps) and major and minor road AADTs for intersections.
- Step 4 – Apply the SPFs to predict total crash frequency for each site during the calibration period. The SPFs from *Safety Analyst* could be used to predict the number of crashes at each site.
- Step 5 – Compute calibration factors for use in Part B predictive model. The calibration factor for a facility type is then defined as the ratio of the total number of observed crashes in the calibration sample to the total number of predicted crashes from Step 4. By estimating a calibration factor, the implicit assumption is that the relationship between observed crashes and predicted crashes is a straight line. Hauer (2013) suggests that the analyst should check whether this relationship is indeed a straight line by estimating the following model:

$$\text{Observed crashes} = C \times (\text{predicted crashes})^d$$

Where, the parameters C (calibration factor) and d can be estimated using regression modeling (e.g., poisson or negative binomial regression). If the relationship between observed crashes and predicted crashes is a straight line, then d will be close to 1.0. Another approach is to estimate C as a function of variables such as AADT, terrain, segment length, etc (this results in a calibration function rather than a calibration factor). This approach is discussed in the *SPF Calibration Guide*.

Steps in Calibrating Project Level SPFs

Based on the discussion in the HSM, following are steps that can be used to calibrate the HSM SPFs:

- Step 1 – Identify facility types for which the applicable Part C predictive model is to be calibrated. As discussed earlier, Part C of the HSM provides predictive methods for three types of facility types: rural two-lane, two-way roads, rural multilane roads, and urban and suburban arterials. For each facility type, models are provided separately for roadway segments and intersections.

- Step 2 – Select sites for calibration of the predictive model for each facility type. The HSM indicates that sites should be selected without regard to the number of crashes. This can be accomplished by selecting sites at random from the pool of available sites. In most states, it may not be appropriate to develop a single calibration factor for a particular facility type across the entire state. Depending on the variation in terrain, climate, topography, crash reporting practices, driver population, animal population, and other factors across the state, multiple calibration factors may be necessary based on somewhat homogeneous subsets of sites of that particular facility type. In addition to considering these factors, Persaud et al., (2002) has argued that different calibration factors may also be necessary for different levels of traffic volume within a particular facility type. With regard to sample sizes needed for calibration, the HSM indicates that 30-50 sites that experience at least 100 crashes per year should be a desirable minimum sample size. This guideline in the HSM was introduced based on engineering judgment and has been challenged by a few researchers (e.g., Banihashemi, 2012). Further details about the sample sizes needed for calibration is available in the upcoming *SPF Calibration Guide*.
- Step 3 – Obtain data for each facility type applicable to a specific calibration period. Data are needed on crash frequency and site characteristics. The list of site characteristics is available from Appendix C of the HSM. The characteristics which the HSM considered to be high impact are called *required* and other characteristics which the HSM considered as being not that sensitive to crash propensity are called *desirable* for which default values are provided in the HSM.
- Step 4 – Apply the applicable Part C predictive model to predict total crash frequency for each site during the calibration period as a whole. The predictive method and the SPFs from Chapters 10, 11, and 12, are used to compute the predicted number of crashes for each site in the calibration sample.
- Step 5 – Compute calibration factors for use in Part C predictive model. The calibration factor for a facility type is then defined as the ratio of the total number of observed crashes in the calibration sample to the total number of predicted crashes from Step 4 (as discussed earlier, a calibration function could be estimated instead of a calibration factor). If the calibrated models are used to estimate the expected number of crashes based on the EB procedure, then the overdispersion parameter of the negative binomial SPF needs to be included in this calculation. For this calculation, both the HSM procedures and *Safety Analyst* make use of the overdispersion parameter that was estimated from the data used to estimate the original SPFs in *Safety Analyst* and the HSM. Some researchers have suggested that the overdispersion parameters should be recalibrated based on the data from the calibration sample (e.g., CDOT, 2009).

It is important to note that in applying these steps, the implicit assumption is that the CMFs in Part C of the HSM (for adjusting the predictions to situations other than the base conditions) are universal, i.e., they are applicable for all the States and are not functions of specific site characteristics. Persaud et al., (2012) and Sacci et al., (2012) have challenged this assumption based on their work when calibrating the HSM prediction models using data from Ontario and Italy, respectively.

Developing SPFs

As discussed earlier, instead of calibrating existing SPFs, an agency may choose to develop their own SPFs in order to improve the accuracy of the predictions. The HSM indicates that jurisdiction-specific

SPFs “are likely to enhance the reliability of the Part C predictive method” (HSM, page A-9). The advantages of jurisdiction-specific SPFs are also discussed in previous studies (e.g., Lu et al., 2012; Sacci et al., 2012). Jurisdiction-specific SPFs also provide the opportunity to examine alternative functional forms (depending on the data) rather than using the default forms in the HSM and *Safety Analyst*. Further discussion is provided in the *SPF Development Guide* that is being developed through funding from FHWA.

In order to develop SPFs, it is necessary, at the minimum, to have an analyst with statistical expertise for estimating simple negative binomial regression models using generalized linear modeling techniques. The analyst also needs experience with the statistical tools discussed earlier. Such experience is available in many Universities and research institutes across the country. Hence, at least a few states have estimated jurisdiction-specific SPFs for network screening, especially for roadway segments (e.g., Srinivasan and Carter, 2011; Tegge et al., 2010).

With respect to project level SPFs, Appendix A to Part C of the HSM outlines two possible approaches for developing SPFs. Following is a quote from page A-10 of the HSM:

“Two types of data sets may be used for SPF development. First, SPFs may be developed using only data that represent the base conditions, which are defined for each SPF in Chapter 10, 11, and 12. Second, it is also acceptable to develop models using data for a broader set of conditions than the base condition. In this approach, all variables that are part of the applicable base-condition definition, but have non-base-condition values, should be included in the initial model. Then, the initial model should be made applicable to the base conditions by substituting values that correspond to those base conditions into the model”.

With either approach, detailed information is necessary about the site characteristics in addition to traffic volume so that it can be determined whether the characteristics of the site correspond to the base condition or not. As discussed earlier, at a minimum, data are needed for the site characteristics that are considered required by the HSM for calibrating the Part C prediction (project level) models. Unlike calibration, developing SPFs requires such data to be available or compiled for a relatively large sample of sites (see Table 1² for sample size estimates). Very few states have such a database. States that do not have a sufficiently detailed database may begin with calibrating SPFs from existing sources but might find it cost prohibitive to develop SPFs.

Steps in Developing SPFs

Below is an overview of steps that are needed in developing SPFs.

- **Step 1 - Identify Facility Type**. The first step is to identify the type of facility for which SPFs will be developed. Depending on whether the SPF is being estimated for project-level analysis or network screening, the jurisdiction can decide which facility types they are most interested in.
- **Step 2 - Compile Necessary Data**. Depending on whether the SPFs will be used for project level analysis or network screening, the data needs are quite different.

² Table 1 is available in Section 5 of this document.

- For network screening SPFs, for each facility type, the number of crashes for each unit (intersection, segment, or ramp), and the traffic volume (AADT) associated with that unit are required. For intersections, it is recommended that AADT for both major and minor roads be available³. If SPFs are to be estimated for a particular crash type or severity, the number of crashes by severity and type will be necessary for each unit.
- For SPFs that will be used for project-level analysis, data on other site characteristics (apart from AADT) will be necessary. A good starting point is the list of variables that are considered required by the HSM for calibrating the Part C prediction models. This list for the different facility types is available in the Appendix to Part C of the HSM.
- At this stage, the sample size that is required for developing jurisdiction specific SPFs needs to be determined. This sample needs to be substantially higher than the minimum sample size suggested by the HSM for calibration (see Table 1).
- A decision needs to be made on how routes will be divided into segments for the analysis. A common approach is to use homogenous segments with respect to site characteristics and traffic volume. This often results in short segments. However, others have suggested using longer, though non-homogenous, sections to account for spatial correlation (Martinelli et al., 2009).
- Step 3 - Determine Functional Form. The SPFs in Part C of the HSM and in *Safety Analyst* are negative binomial regression models with a log-linear relationship between crash frequency and site characteristics. However, that may not be most appropriate form (Hauer, 2004; Kononov et al., 2011). Different types of exploratory analysis need to be conducted to determine the appropriate functional form of the relationship between crash counts and independent variables, and the possible need for including interaction terms between independent variables. Examples include using plots to illustrate the functional form of the relationship between crash counts and different independent variables and a discussion of methods such as classification and regression trees (CART) to identify which independent variables and interactions are relevant in the model. This step is easier to accomplish for network screening SPFs where fewer variables (usually just AADT) are involved.
- Step 4 - Develop the SPF. A number of statistical tools (statistical software) are available to develop SPFs. Common ones include SAS, STATA, and GENSTAT (all commercially available software packages). However, other software tools including R, an open source programming language, and Microsoft Excel, can be used as well. It is, however, important to consider in the modeling effort that crashes typically follow a negative binomial distribution, not a normal distribution.
- Step 5 - Conduct Model Diagnostics. There are different steps involved in conducting effective diagnostics to determine if the estimated SPF is reasonable. These include checking the sign of the parameters' coefficients, examining residuals via residual plots and cumulative residual plots (i.e., CURE plots), and identifying potential outliers using Cook's D or other tools, and examining goodness-of-fit measures.
- Step 6 - Re-estimate the SPF. Based on the results of Step 5, the SPF may have to be re-estimated using a different statistical model or functional form. The SPF may also need to be re-estimated after removing outliers that were identified in the diagnostics step.

³ There has been some discussion in the highway safety research community on whether SPFs for network screening will be significantly improved by including other explanatory variables in addition to traffic volume and segment length – Srinivasan et al., (2011) provides some discussion on this topic.

5. Decision Process: How an Agency Obtains SPFs

An agency will have to undergo a process for determining the appropriate course to take when deciding on the final SPFs to use. This may involve only calibrating existing SPFs or going further to develop their own SPFs. Several factors can affect this process, including intended use of the SPF, intended facility type, available sample size, quality of existing roadway data, and available analytical expertise. The process is outlined below.

Step-by-Step Process

This process outlines the steps that an agency needs to take in order to obtain the final SPF to be used in its jurisdiction. This process begins with SPF calibration and then moves to SPF development if the calibration is deemed too low quality.

Step 1. Determine intended use of SPF.

As discussed in Section 3 of this guidebook, the two main uses of SPFs in this context are *network screening level* and *project level*. Network screening level SPFs are used to identify sites that may have the best potential for improvements. Project level SPFs are used to determine the safety impacts of design changes at the project level. The agency must determine the intended use of the SPF. For more description of these uses, see Section 3.

Step 2. Determine facility type.

The agency must determine which facility type will be addressed by the SPF. Facility types include roadway segments, intersections, and ramps. The type of facility to be addressed by the SPF will affect the type of data to be collected and will direct the identification of existing SPFs. Additionally, it is conceivable that an agency may decide to develop jurisdiction-specific SPFs for certain facility types, but calibrate existing SPFs (i.e., from the HSM, *Safety Analyst*, or other sources) for other facility types. Developing SPFs for project-level analysis will require assembling a database with sufficient number of sites with detailed information on site characteristics. Depending on the variables available in the State's roadway inventory files, the process of assembling a database may be easier for some facility types than for others.

Step 3. Identify existing SPF.

The agency must identify an existing SPF according to the intended use and facility type. As described in Section 4, existing SPFs for network screening may be obtained from *Safety Analyst*. Existing SPFs for project level analysis may be obtained from Part C of the Highway Safety Manual. Appendix A lists the types of facilities for which SPFs are available in these resources (e.g., rural two-lane roads, etc.).

Step 4. Consider sample size necessary for calibrating SPF.

The agency must consider what sample size is required to calibrate the SPF. For project level SPFs (as determined in Step 1), the HSM specifies that 30 to 50 sites with at least 100 crashes per year would be a reasonable sample for calibrating the HSM SPFs (the upcoming *SPF Calibration Guide* provides guidance on the number of sites and crashes needed to estimate the calibration factor to a given

accuracy). For facility types that are fairly common (e.g., rural two-lane roads), identifying the site needed for calibration would be a fairly easy task. For facility types that may be less common (e.g., rural four-lane undivided), this could be more challenging and time consuming. In some cases, the number of sites or miles of a particular facility type may be so small that developing a calibration factor for that facility type would be of low priority, and the agency should consider whether it is worth the cost of undergoing the calibration process for that facility type.

For urban facilities, this target crash number of 100 crashes (based on the HSM) would likely be met with a small number of sites (given the higher traffic and crash frequencies at urban sites). For rural facilities, it is likely that the agency would need to identify a larger group of sites in order to meet the required minimum number of crashes per year to establish a good statistical base for calibration.

It should be noted that this group of sites for calibration should NOT be selected on the basis of crash counts. That is, the agency should not hand pick a group of high crash sites simply to meet the minimum crash frequency requirement. Doing so would strongly bias the calibration process. Rather, the selection should be random from the population of the appropriate facility type (i.e., random selection of X number of sites from the entire list of rural four-leg signalized intersections throughout the agency). A procedure for randomly selecting sites for calibration is discussed in the upcoming *SPF Calibration Guide*.

With respect to network screening SPFs, these SPFs will be used on a broad scale basis across the whole network. Thus, all sites of the particular facility type (as determined in Step 2) over the entire network should be used for the calibration effort.

Step 5. Consider roadway data necessary for calibrating SPF.

The requirements for roadway data depends on the intended use of the SPF (product of Step 1) and the intended facility type (product of Step 2). In general, calibrating project level SPFs requires more detailed data than calibrating network screening level SPFs. For project level SPFs, an agency could calibrate an SPF from the HSM. Calibrating the HSM SPFs requires detailed roadway data for calculating the various crash modification factors (CMFs) that are part of the HSM predictive process. The list of site characteristics is available from the Appendix to Part C of the HSM. The characteristics which the HSM considered to be high impact are called *required* and other characteristics which the HSM considered as being not as sensitive to crash propensity are called *desirable* (default values for desirable characteristics are provided in the HSM).

For calibrating network screening level SPFs, the data requirements would be less stringent, including only AADT and segment length (for roadway segments and ramps) and major and minor road AADT for intersections. The data requirements are less detailed, since the intended use of network screening level SPFs is on the broad scale across the whole network in order to select sites with promise for safety improvements. Traffic volume data for roadway segments is available in most states. On the other hand, many states do not have an inventory of intersections and ramps. Some have an inventory of intersections on their state maintained roads but may not have minor road AADT, especially if the minor roads are not state maintained. If this is the case, then the time required for site identification and data

collection will increase. Appendix B discusses the major considerations in building an intersection inventory and some discussion of the cost involved.

The agency must evaluate the roadway data requirements and compare to its own roadway inventory. If the level of detail available in the agency's existing roadway inventory is high, then the work required to assemble the data necessary for calibration will be minimal. However, if the existing roadway inventory has only very basic data, then a more significant effort will be required to assemble the necessary data. Table 1 provides an estimate of the hours required for data collection.

Step 6. Calibrate existing SPF.

Once the previous steps have been executed, and the agency has determined the intended use of the SPF, identified the facility type to be addressed, identified an SPF from the HSM or Safety Analyst, and considered the requirements for sample size and roadway data, the agency can undertake the calibration process. Calibration can be done by staff with limited to no statistical experience and can be implemented using spreadsheet software such as Microsoft Excel. See section 4 for step-by-step description of the calibration process. The result of this process is a calibration factor that is used to adjust the crash predictions of the SPF to be accurate to the agency's jurisdiction. As discussed earlier, separate calibration factors may be needed for each specific terrain type, region, climate, or AADT category. Further guidance for estimating the calibration factor along with its standard deviation is available in the upcoming *SPF Calibration Guide*.

Step 7. Assess quality of calibration factor/function.

Once the calibration factor has been developed, the agency must assess the quality of the calibration process. There are many ways to do this. One is the value of the calibration factor itself. If the total SPF crash predictions match exactly to the agency's total number of observed crashes, then the process would produce a calibration factor of 1.0. If the SPF under predicts an agency's crashes, the calibration factor would be greater than 1.0. If the SPF over predicts, the calibration factor would be less than 1.0. If the calibration factor is very different from 1.0 (i.e., much less or much greater), this would indicate that the agency's crash experience is much different from the data that were used to estimate the original SPFs.

Another way to assess the quality of calibration process is to use goodness of fit (GOF) tests such as cumulative residual (CURE) plots. CURE plots and other GOF tests are discussed in Hauer (2013) and the *SPF Development guide*. Further guidance on assessing the quality of the calibration is provided in the upcoming *SPF Calibration Guide*.

For project level SPFs, if the calibration factor is of good quality, then it can be used along with the HSM predictive methodology to conduct project level analysis. For network screening SPFs, if the quality of the calibration factor is considered good, then it can be used for network screening. If the calibration factor is not of good quality, then the agency should follow Steps 8-10 below to develop SPFs using the procedure discussed in the upcoming *SPF Development Guide*.

Step 8. Consider statistical expertise necessary for developing SPF.

Calibrating existing SPFs and developing new SPFs require different skill levels. As mentioned in Step 6, calibration requires little to no statistical experience. However, developing SPFs requires personnel with a background in statistical modeling. Agencies without such in-house expertise might consider hiring a consultant (e.g., university consultants).

Step 9. Consider sample size necessary for developing SPF.

As compared to calibrating SPFs, developing SPFs would typically require a larger sample. The amount of sample required depends on the intended use (product of Step 1). For project level SPFs, the agency should identify 100-200 intersections (for intersections models) or 100-200 miles (for segment models) with at least 300 crashes per year for the whole group.

With respect to network screening SPFs, these SPFs will be used on a broad scale basis across the whole network. Thus, all sites of the particular facility type (as determined in Step 2) over the entire network should be used for the calibration effort. However, if the agency cannot assemble a group of at least 100-200 intersections or 100-200 miles with at least 300 crashes per year for the total group, then the reliability of SPF development may be questionable.

Step 10. Determine crash type to be addressed by SPF.

When conducting SPF calibration, only total crash counts are typically used to calculate the calibration factor. However, when developing SPFs, there may be separate models to address each crash type. That is, one SPF could be developed to predict total crashes and a separate SPF could be developed to predict run-off-road crashes. The agency must determine which crash type will be addressed by the SPF. Multiple crash types may require multiple SPFs to be developed. Further discussion of this topic will be available in the *SPF Development Guide*.

Step 11. Develop SPF.

Once Steps 8-10 have been executed, the agency can undertake the development of the SPF. Section 4 provides a description of the basic steps involved in developing the SPF. Further detailed guidance on developing an SPF will be provided in the *SPF Development Guide*.

Staff Time Required for Calibration and Development

Many agencies will want to have an idea of the cost of the effort to calibrate and/or develop SPFs. Table 1 provides the estimated ranges of staff time required for each endeavor. The staff time required to collect and prepare the data can range greatly depending on the following factors:

- *Whether one or many SPFs are being addressed.* If many SPFs are being calibrated or developed in the same project, then the data collection is more efficient per SPF, since the data collector can obtain data on many types of sites during the same effort. For instance, a data collector who is collecting data on rural two-lane road segments can also gather information on rural two-lane road intersections with minimal additional effort.
- *Available data in existing roadway inventory.* If most of the required data elements are contained in the agency's existing inventory, the data collection time will be minimal. However,

the fewer the data elements available in the inventory, the greater is the time needed to assemble the required data. Methods for collecting the data may involving aerial photos, online imagery, construction plans, and/or field visits.

Table 1. Level of Effort Estimates for SPF Calibration and Development

Intended Use	Process	Sample needed	Staff hours needed - data collection and preparation (per SPF)	Staff hrs needed - statistical analyst (per SPF)
Project level	Calibrate SPF	30-50 sites; at least 100 crashes per year for total group ^a . At least 3 years of data are recommended.	150 to 350	n/a ^d
Project level	Develop SPF	100-200 intersections or 100-200 miles; at least 300 crashes per year for total group ^c . At least 3 years of data are recommended.	450 to 1050	16 to 40
Network screening	Calibrate SPF	Must use entire network to be screened. No minimum sample specified. At least 3 years of data are recommended.	24 to 40 ^b	n/a ^d
Network screening	Develop SPF	Must use entire network to be screened. Minimum sample would be 100-200 intersections or 100-200 miles; at least 300 crashes per year for total group ^c . At least 3 years of data are recommended.	24 to 40 ^b	8 to 24

Notes:

^aThis is based on the guidance from the HSM. The *SPF Calibration Guide* will provide further guidance on this issue.

^bIn estimating the staff hours for data collection and preparation for network screening, it was assumed that all the necessary data are available in the jurisdiction’s inventory file. All state DOTs have some form of basic roadway segment inventory due to the requirements of the Highway Performance Monitoring System (HPMS). However, the situation is different for intersections. Very few states have an inventory of intersections along their public roads. Appendix B discusses the major considerations in building an intersection inventory and some discussion of the cost involved.

^cThe sample size estimates are based on the judgment of the project team. Methods for estimating the sample size for poisson type regression models are available (e.g., Shieh, 2001), but the project team did not feel that such methods were directly applicable for this situation.

^dNo statistical analytical experience is required for calibration.

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Appendix A: Roadway and Intersection Types for which SPFs are provided in the HSM (1st Edition) and *Safety Analyst*

Facility Types Included in Part C of the HSM (1st Edition)

For roadway sections, Part C of the HSM provides SPFs for the following 8 types:

- Rural two lane roads
- Rural four-lane divided
- Rural four-lane undivided roads
- Two lane urban and suburban arterials,
- Three lane (with center TWLTL) urban and suburban arterials,
- Four lane divided urban and suburban arterials,
- Four lane undivided urban and suburban arterials,
- Five lane (with center TWLTL) urban and suburban arterials.

For intersections, SPFs are available for the following 9 types:

- Three-leg minor road stop controlled intersections on rural two lane roads
- Four-leg minor road stop controlled intersections on rural two lane roads
- Four-leg signalized intersections on rural two lane roads
- Three-leg intersections on rural four lane roads
- Four-leg minor road stop controlled intersections on rural four lane roads
- Three-leg minor road stop controlled intersections on urban and suburban arterials
- Four-leg minor road stop controlled intersections on urban and suburban arterials
- Three-leg signalized intersections on urban and suburban arterials
- Four-leg signalized intersections on urban and suburban arterials

Facility Types in Safety Analyst

For roadway segments, SPFs are available for the following 17 types:

- Rural two-lane roads
- Rural multilane undivided roads
- Rural multilane divided roads
- Rural freeways – 4 lanes
- Rural freeways – 6+ lanes
- Rural freeway segments within an interchange area – 4 lanes
- Rural freeway segments within an interchange area – 6+ lanes
- Urban two-lane arterial segments
- Urban multilane undivided arterial segments
- Urban multilane divided arterial segments

- Urban one-way arterial segments
- Urban freeway segments – 4 lanes
- Urban freeway segments – 6 lanes
- Urban freeway segments – 8+ lanes
- Urban freeway segments within an interchange area – 4 lanes
- Urban freeway segments within an interchange area – 6 lanes
- Urban freeway segments within an interchange area – 8+ lanes

For intersections, SPFs are available for the following 12 types:

- Rural three-leg intersections with minor-road stop control
- Rural three-leg intersections with all-way stop control
- Rural three-leg signalized intersections
- Rural four-leg intersections with minor-road stop control
- Rural four-leg intersections with all-way stop control
- Rural four-leg signalized intersections
- Urban three-leg intersections with minor-road stop control
- Urban three-leg intersections with all-way stop control
- Urban three-leg signalized intersections
- Urban four-leg intersections with minor-road stop control
- Urban four-leg intersections with all-way stop control
- Urban four-leg signalized intersections

For ramps, SPFs are available for the following 16 types:

- Rural diamond off-ramps
- Rural diamond on-ramps
- Rural parclo loop off-ramps
- Rural parclo loop on-ramps
- Rural free-flow loop off-ramps
- Rural free-flow loop on-ramps
- Rural free-flow outer connection ramps
- Rural direct and semidirect connection ramps
- Rural diamond off-ramps
- Rural diamond on-ramps
- Rural parclo loop off-ramps
- Rural parclo loop on-ramps
- Rural free-flow loop off-ramps
- Rural free-flow loop on-ramps
- Rural free-flow outer connection ramps
- Rural direct and semidirect connection ramps

Appendix B. Developing an Intersection Inventory

Developing network screening SPFs requires an existing inventory for the facility of interest. For roadway segments, this is not typically an issue. All state DOTs have some form of basic roadway segment inventory, due to the requirements of the Highway Performance Monitoring System (HPMS). However, the situation is different for intersections. Very few states have an inventory of intersections along their public roads. States who are considering the use of network screening SPFs may be interested in exploring the creation of an intersection inventory, particularly the staff time and cost that would be necessary to develop such an inventory. Below are listed several of the major considerations in building an intersection inventory and some discussion of the cost involved.

Location of Intersections

Determining the location of each intersection is the most critical element for any intersection inventory. Two of the most common ways of referencing an intersection location are a Linear Referencing System (LRS) or Geographic Information System (GIS). Typically, an agency would use the same location system that is used for their roadway segment inventory. Locating and assigning a unique ID to each intersection is a substantial task. Ohio DOT developed a semi-automatic in-house process to create the initial intersection inventory file (i.e., locations and unique identifiers). They report that it took approximately 3 person months to develop the semi-automated process, but that the process was designed to be used on an annual basis and takes 2-3 hours to run each time. Other agencies who keep their roadway inventory in GIS have used built-in GIS tools to automatically create points where roadway lines intersect. They then manually identified which points were intersections and assigned an appropriate ID number. The amount of time required for this manual identification is unknown to the authors.

Traffic Volume

Another crucial piece of an intersection inventory is traffic volumes on both the major and minor roads of the intersection. This information can often be gleaned from the roadway segments adjacent to the intersection. This is usually not an issue for the major road (especially, if the major road is state maintained), but it can be a problem for obtaining volumes on the minor roads. The state roadway inventory may not contain volume data on the minor road of the intersection, especially if it is not a state-owned road.

Ohio DOT reports that they use a hierarchical approach in assigning traffic volume to the intersection file. First, they use the volume information from the adjacent roadway sections. If that is not available for one or more intersection legs, they obtain any volume information that can be supplied from Metropolitan Planning Organization (MPO) data. If that is not available, they assign a traffic volume value using default values for functional class by county.

Geometry and Traffic Control

The other major piece of information is the geometry and traffic control of the intersection. This is necessary for categorizing intersections (SPFs are developed according to intersection type). Ohio DOT

obtained this information by manual effort, using interns to collect the data. They estimate approximately 3000 hours were necessary to collect this information (along with other intersection-level characteristics that were of interest). This was performed for a total of 47,000 intersections that lay on Ohio state-maintained roads, for an average cost of \$1.30 per intersection (assuming intern pay is \$20/hr).

The FHWA Office of Safety recently released a report containing estimated costs for collecting basic inventory variables, known as the Model Inventory Roadway Elements (MIRE) Fundamental Data Elements (Fiedler et al., 2013). They estimate that the cost of collecting basic geometry and traffic control would be approximately \$1.00 per intersection.

References

Fiedler, Rebecca, Kim Eccles, Nancy Lefler, Ana Fill, and Elsa Chan. *MIRE Fundamental Data Elements Cost-Benefit Estimation*. Final Report, Contract DTFH61-11-C-00050, March 2013.

Appendix C. Recent SPF Development Efforts from States

Following is a brief description of recent jurisdiction specific SPF development efforts (rather than the calibration of existing SPFs) from States. These were compiled based on a review of the published literature. The focus was on SPF development for the purpose of network screening or project level analysis. In addition to the states listed here, there are states that are in the process of developing SPFs (examples include Alabama, Louisiana, and Washington).

Colorado

Persaud and Lyon, Inc. and Felsburg Holt and Ullevig, *Safety Performance Functions for Intersections*, Report CDOT-2009-10, Developed for Colorado Department of Transportation, Denver, Colorado, December 2009.

This study developed SPFs for 10 intersection categories:

- Urban 4-Lane Divided Signalized 4-Leg
- Urban 6-Lane Divided Signalized 4-Leg
- Urban 4-Lane Divided Signalized 3-Leg
- Urban 2-Lane Undivided Unsignalized 4-Leg
- Urban 4-Lane Divided Unsignalized 4-Leg
- Urban 2-Lane Undivided Unsignalized 3-Leg
- Urban 4-Lane Divided Unsignalized 3-Leg
- Urban 4-Lane Undivided Unsignalized 4-Leg
- Urban 2-Lane Divided Unsignalized 3-Leg
- Urban 4-Lane Undivided Unsignalized 3-Leg

At least 5 years of data were available for each intersection that was used in the analysis. SPFs were estimated for total and injury and fatal crashes. CURE plots and other goodness of fit measures were used to assess the validity of the SPFs. Since the SPFs just used major and minor road AADT data, they could be used for network screening.

Florida

Lu, J., A. Gan, K. Haleem, P. Alluri, and K. Liu, Comparing Locally-Calibrated and Safety Analyst Default Safety Performance Functions for Florida's Urban Freeways, *Presented at the 91st Annual Meeting of the Transportation Research Board*, January 2012.

SPFs were estimated for network screening consistent with the format in Safety Analyst. SPFs were estimated for total and fatal and injury crashes for the following road types:

- 4 lane urban freeways outside influence of interchanges
- 4 lane urban freeways within the influence of interchanges
- 6 lane urban freeways outside influence of interchanges
- 6 lane urban freeways within the influence of interchanges

- 8+ lane urban freeways outside influence of interchanges
- 8+ lane urban freeways within the influence of interchanges

Illinois

Tegge, R.A., J. Jang-Hyeon, and Y. Ouyang (2010), *Development and Application of Safety Performance Functions for Illinois*, Research Report ICT-10-066, Illinois Center for Transportation, Civil Engineering Studies, March 2010.

SPFs were estimated for roadway segments and intersections on state-maintained roads. SPFs were estimated for fatal, type A injury, type B injury, and fatal and injury combined. The main focus was to estimate the SPFs for network screening that could be used within *Safety Analyst*. For roadway segments, SPFs were estimated for the following roadway types:

- Rural Two-Lane Highway
- Rural Multilane Undivided Highway
- Rural Multilane Divided Highway
- Rural Freeway, 4 Lanes
- Rural Freeway, 6+ Lanes
- Urban Two-Lane Highway
- Urban One-Way Arterial
- Urban Multilane Undivided Highway
- Urban Multilane Divided Highway
- Urban Freeway, 4 Lanes
- Urban Freeway, 6 Lanes
- Urban Freeway, 8+ Lanes

For intersections, SPFs were estimated for the following types:

- Rural Minor Leg Stop Control
- Rural All-Way Stop Control
- Rural Signalized Intersection
- Rural Undetermined
- Urban Minor Leg Stop Control
- Urban All-Way Stop Control
- Urban Signalized Intersection
- Urban Undetermined

In addition to the SPFs for network screening, an SPF was estimate for KAB injury crashes for roadway segments. This SPF included information about access control, shoulder width and type, lane width, median type and other segment characteristics. This SPF is a possible starting point for project level analysis.

North Carolina

Srinivasan, R. and D. Carter, *Development of Safety Performance functions for North Carolina*, Report FHWA/NC/2010-09, Submitted to North Carolina Department of Transportation, December 2011.

All SPFs predicted the number of crashes per mile as a function of AADT consistent with the functional form in *Safety Analyst*. North Carolina specific SPFs were estimated for the following crash types:

- Total crashes
- Injury and fatal crashes (K, A, B, C)
- Injury and fatal crashes (K, A, B)
- Property damage only (PDO) crashes
- Lane departure crashes
- Single vehicle crashes (including animal crashes)
- Multi vehicle crashes
- Wet crashes
- Night crashes – This included crashes with Ambient Light = (4) Dark – lighted roadway, or (5) Dark – roadway not lighted, or (6) Dark – unknown lighting

SPFs were estimated for the following roadway types:

- Rural Two Lane Roads
- Rural Freeways - 4 lanes - outside the influence of interchanges
- Rural Freeways – 6+ lanes - outside the influence of interchanges
- Rural Freeways - 4 lanes - within the influence of interchanges
- Rural Freeways – 6+ lanes - within the influence of interchanges
- Rural Multilane Divided Roads
- Rural Multilane Undivided Roads
- Urban Two Lane Roads
- Urban Freeway - 4 lanes - outside the influence of interchanges
- Urban Freeway - 6 lanes - outside the influence of interchanges
- Urban Freeway - 8+ lanes - outside the influence of interchanges
- Urban Freeway - 4 lanes - within the influence of interchanges
- Urban Freeway - 6 lanes - within the influence of interchanges
- Urban Freeway - 8+ lanes - within the influence of interchanges
- Urban Multilane Divided Roads
- Urban Multilane Undivided Roads

In addition to these SPFs for network screening, SPFs were estimated for rural two lane roads that included terrain, shoulder width, shoulder type, in addition to AADT. These SPFs are possible starting points for project level analysis.

Utah

Brimley, B.K., M. Saito, and G.G. Schultz, Calibration of Highway Safety Manual Safety Performance Function: Development of Models for Rural Two-Lane Two-Way Highways, *Transportation Research Record* 2279, pp. 82-89.

SPFs for total crashes were estimated for rural two lane roads. The independent variables considered included AADT, information about whether passing was permitted, whether shoulder rumble strips were present, percent multiple-unit trucks, and speed limit. Different models were examined and a model

was selected based on the Bayesian Information Criterion (BIC). The recommended model could be used for network screening and could be a starting point for project level analysis.

Virginia

Garber, N.J. and G. Rivera, *Safety Performance Functions for Intersections on Highways Maintained by the Virginia Department of Transportation*, FHWA/VTRC 11-CR1, Virginia Department of Transportation, October 2010.

SPFs were estimated primarily for use in *Safety Analyst* for network screening. SPFs were estimated for the following intersection types:

- Urban 4 leg signalized
- Urban 4 leg minor road stop controlled
- Urban 3 leg signalized
- Urban 3 leg minor road stop controlled
- Rural 4 leg signalized
- Rural 4 leg minor road stop controlled
- Rural 3 leg signalized
- Rural 3 leg minor road stop controlled

SPFs were estimated total and fatal and injury crashes. Separate SPFs were also estimated for different regions in Virginia.