Safety Performance Functions

FINAL REPORT

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16. Abstract

This project developed safety performance functions for roadway segments and intersections for two-lane rural highways in Pennsylvania. The statistical modeling methodology was consistent with that used in the first edition of the American Association of State Highway and Transportation Officials' *Highway Safety Manual*. Two realistic case study examples are provided to illustrate how to use the safety performance functions developed in this project.

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INTRODUCTION

The American Association of State Highway and Transportation Officials' (AASHTO) *Highway Safety Manual* (HSM) provides transportation professionals with the tools necessary to quantify the safety performance of planned or existing highways. One set of tools available in the current edition of the HSM are safety performance functions (SPFs) for rural two-lane, rural multi-lane, and urban and suburban arterials. The HSM also provides a detailed calibration method to adapt each algorithm to local conditions since the data used to develop the crash prediction algorithms were not acquired from Pennsylvania and thus do not reflect Pennsylvania driving conditions. Alternatively, the HSM indicates that developing SPFs using local data will provide more reliable crash frequency estimates than applying the calibration procedure.

In light of this, the objectives of this project are to develop SPFs for rural two-lane road segments and intersections in Pennsylvania. Statistical models for total crash frequency and fatal and injury crash frequency were created using data from all state-owned two-lane rural roadways with three-digit or lower state route numbers. To ensure that the models developed in this research were similar to those presented in the HSM, the same statistical analysis methods were used.

The report is organized into four subsequent sections. The first describes the data elements and structures that were acquired to estimate the statistical models of crash frequency. The following two sections describe the estimation of roadway segment SPFs and intersection SPFs, respectively. The final section of this report includes two realistic case study examples to illustrate how the SPFs can be used to assess the safety performance of two-lane rural highway segments and intersections, respectively, in Pennsylvania.

DATA COLLECTION

The first part of this section includes a description of the PennDOT Roadway Management System (RMS) data files that were acquired to develop the SPFs and how these files were organized for statistical modeling purposes. These data were supplemented with additional elements that were collected using PennDOT's online vehicle photolog system and Google Earth, which are described in Appendices A and B, respectively. The last part of this section includes information concerning the electronic crash data that were used to develop the roadway and intersection SPFs.

Roadway Management System Data

The RMS data files include information about the roadway cross-section, traffic volume, access control, functional classification, posted speed limit, and intersection locations and traffic control. These data are codified based on PennDOT's linear referencing system, which is defined by the county, state route, and segment number. Two data files (for the years 2008 and 2012) were acquired from PennDOT for modeling purposes. These two data files were initially compared to determine if segments or intersections were added or deleted during this time period perhaps due to new roadway construction, major reconstruction or changes in the functional classification of a segment. For the most part, roadway infrastructure elements in the data files (e.g., number of lanes, lane width, shoulder type, shoulder width, divisor type, and divisor width) remained unchanged between the years 2008 and 2012; however, any differences were identified. Since a comparison of the segment and intersection data in the 2008 and 2012 files revealed that few differences existed between the two files, the 2012 file was used as the base file since it was the most recently updated.

The only variables that changed significantly across the files were the traffic volumes, expressed as average annual daily traffic (AADT) in units of vehicles per day. To account for changing traffic volumes for the interim years between 2008 and 2012, the research team used linear interpolation of these known volumes. As historical crash data was available starting from 2005, linear extrapolation was used to estimate traffic volumes for the years between 2005 and 2008.

Intersection location information was acquired from the PennDOT RMS Intersection data files. The RMS Intersection data files include the county, state route number, segment, and offset where two roadways on the state-owned roadway network intersect. This intersection location information was appended to the segment data. After merging the RMS segment data with the RMS Intersection data, two separate data files were created for the SPF development process. The first file was used for the development of SPFs on roadway segments, and included the following data elements:

- Linear reference information (county, route, and segment)
- Segment length
- Average annual daily traffic (vehicles/day)
- Commercial vehicle traffic (trucks/day)
- Paved roadway width (including all travel lanes)
- Number of travel lanes in both directions
- Posted speed limit
- Divisor type
- Left- and right-shoulder type
- Left- and right-shoulder paved width (feet)
- Left- and right-shoulder total width

The second file was used for the development of SPFs at intersections and was composed of only the relevant data from intersection locations. These data included the type of control present at each intersection as well as the segment-level data listed above for each intersecting roadway in the intersection data analysis files.

There are several supplemental data elements that were collected as part of this project to enable inclusion of additional roadway and roadside features in the SPFs. At the segment-level, these included the roadside hazard rating, presence, radius and length of horizontal curves, presence of passing zones, and the presence of various low-cost safety improvements (i.e., shoulder or centerline rumble strips, horizontal curve warning pavement markings, intersection warning pavement marking, and aggressive driving dot pavement markings). For the intersection data files, the additional elements included intersection skew angle, presence of auxiliary lanes on intersections approaches (i.e., left- or right-turn lanes) and the presence of crosswalks on any intersection approach. The presence and type of the traffic control at each intersection was also verified during this stage of the data collection process. Each of these supplemental data collection strategies are described below.

Supplemental Roadway and Intersection Data Elements

This part of the data collection plan is organized into two parts. The first describes the data elements that were collected and codified using PennDOT's online video photolog system. The second describes the data elements that were collected using the Google Earth web-based tool. Appendix A and Appendix B include the instructional guides for the online video photolog and Google Earth data collection methods, respectively.

Online Video Photolog Data Collection

PennDOT's video photolog system can be found online at the following link:

http://www.dot7.state.pa.us/VideoLog/Open.aspx

The web-based application contains a forward-looking view of the roadway and roadside from a driver's perspective. The distance between consecutive images varies from 21 to 210 feet. In addition to the forward-looking display, a map of the segment within the roadway network is displayed within the video photolog application.

Both roadway segment and intersection details were collected using the online video photolog system. The segment data included:

- Roadside hazard rating (RHR): estimated on the 1 to 7 scale proposed by Zegeer et al. (1986)
- Presence of passing zones within the segment.
- Presence of low-cost safety improvements, such as: centerline and shoulder rumble strips on roadway, horizontal curve warning pavement markings, aggressive driving dots, and intersection warning pavement markings.
- Driveway density: the number of driveways or intersections along a segment that are not included in the state-owned intersection analysis database.

Each of these data elements were coded into the RMS data files that are described above for each two-lane rural highway segment. The intersection data elements that were collected using the on-line video photolog system included:

- Presence of intersection auxiliary lanes: left- or right-turn lanes

- Presence of pedestrian crosswalk on intersection approach.
- Verification of the type of intersection traffic control: signalized or stop-controlled intersections

Each of these data elements were coded into the RMS Intersection data files that are described above.

Appendix A of this report includes an instructional guide that describes the data collection procedure and was used to ensure inter-rater consistency among the data collection team for the RHR.

<u>Google Earth Data Collection</u>

The Google Earth tool provides high-quality satellite imagery of Pennsylvania and built-in functions to measure features to scale. This satellite imagery was used to collect horizontal curve and intersection skew angle data. The radius (or degree) and length of each horizontal curve on the two-lane rural roadways were collected at the segment-level. In cases where no horizontal curve existed within a segment or where the entire length of a horizontal curve was contained within the limits of a single segment, these data were coded as such for that particular segment. When horizontal curves crossed into adjacent roadway segments, the length of each curve within each of the adjoining segments was noted. This enabled the research team to use an alignment index to assess the association between horizontal curvature and crash frequency and severity when estimating the SPFs. The horizontal alignment indexes that were considered by the research team included (Fitzpatrick et al., 1999):

$$\frac{\sum DC_i}{L} \tag{1}$$

$$\frac{\sum CL_i}{L} \tag{2}$$

$$\frac{\sum R_i}{n} \tag{3}$$

where:

DC_i = degree of curve for curve i (i = 1, 2, …, n) [degrees];
L = length of segment (miles);
CL_i = length of curve for curve i (i = 1, 2, …, n) [miles];
R_i = Radius of curve i (i = 1, 2, …, n) [ft]; and,
n = number of horizontal curves per segment

Intersection skew angle was determined by using a protractor to measure the angle of the intersecting roadways from Google Earth images. These data were then added to the intersection SPF analysis database.

Appendix B of this report includes an instructional guide that describes the data collection procedure and was used to ensure inter-rater consistency among the data collection team for the horizontal curve and intersection skew angle data elements.

Electronic Crash Data

The research team used the most recent eight years of crash data (2005 through 2012, inclusive) to estimate the roadway segment and intersection SPFs. These data files contained information about the event, driver, and vehicle occupants for each reported crash on the state-owned highway system in Pennsylvania. Only event information was used for the current study. The following data elements were used when developing the segment-level analysis database:

- Crash location: county, state route, segment, and offset
- Crash date: month, day, year
- Crash type: rear-end, head-on, angle, sideswipe, hit fixed object, hit pedestrian, other
- Intersection type: mid-block, four-way intersection, "t" intersection, "y" intersection, traffic circle/roundabout, multi-leg intersection, railroad crossing, other
- Location type: underpass, ramp, bridge, tunnel, toll booth, driveway or parking lot, ramp and bridge
- Work zone type: construction, maintenance, utility company
- Injury severity: fatality, major injury, moderate injury, minor injury, no injury

Several of the crash data elements were used to identify crashes occurring on roadway segments and intersections of interest for the present study. For example, crashes occurring on ramps were used as a check to ensure that the RMS files have correctly eliminated ramps from the analysis database. Crashes in construction work zones were not included in the analysis files as these conditions are temporary.

Crash data were merged with the RMS and supplemental data files based on the location of the crash (county, route, and segment). Crash counts (total, total for each severity level, and total for each crash type) for each roadway segment and intersection were generated for each analysis year. Locations that did not experience a crash during any one or more years were retained in the analysis database and a zero crash count was noted for these locations.

ROAD SEGMENT SAFETY PERFORMANCE FUNCTIONS

This section of the report describes the SPFs developed for rural two-lane highway segments in Pennsylvania. The first part of this section describes the statistical analysis methodology used to generate the safety performance functions. The second part briefly summarizes the data used for model estimation, noting that the data collection methods that were used to assemble the data analysis files were described in the previous section of this report. Statistical models are then reported for total crashes and for total fatal and injury crashes. An interpretation of the regression coefficients is also included in the last part of this section.

Statistical Modeling Methodology

Several cross-sectional modeling approaches were considered to estimate the roadway segment SPFs in the current study. However, in an effort to be consistent with the first edition of the HSM, negative binomial regression was used. Such an approach models the expected number of crashes per mile per year in each roadway segment as a function of one or more explanatory variables. This is a very common approach to model roadway segment crash frequency (e.g., Miaou, 1994; Shankar et al., 1995; Chang et al., 2005; El-Basyouny and Sayed, 2006) because it accounts for the overdispersion that is often observed in crash data. Overdispersion results from the variance exceeding the mean in the crash frequency distribution. The general functional form of the negative binomial regression model is:

$$\ln \lambda_i = \beta X_i + \varepsilon_i \tag{4}$$

where:

- λ_i = expected number of crashes on roadway segment *i*;
- β = vector of estimable regression parameters;
- X_i = vector of geometric design, traffic volume, and other site-specific data; and,
- ε_i = gamma-distributed error term.

The mean-variance relationship for the negative binomial distribution is:

$$Var(y_i) = E(y_i)[1 + \alpha E(y_i)] \tag{5}$$

where:

- $Var(y_i)$ = variance of observed crashes y occurring on roadway segment *i*;
- $E(y_i)$ = expected crash frequency on roadway segment *i*; and,
- α = overdispersion parameter.

The appropriateness of the negative binomial (NB) regression model is based on the significance of the overdispersion parameter. When α is not significantly different from zero, the negative binomial model reduces to the Poisson model. For all the models that were estimated, the estimate of α is reported to verify the appropriateness of the negative binomial approach.

The method of maximum likelihood is used to estimate the model parameters. This method estimates model parameters by selecting those that maximize a likelihood function that describes the underlying statistical distribution assumed for the regression model. The likelihood function for the NB model that was used in this study is shown in equation (6):

$$L(\lambda_i) = \prod_{i=1}^{N} \frac{\Gamma(\theta + y_i)}{\Gamma(\theta) y_i!} \left[\frac{\theta}{\theta + \lambda_i}\right]^{\theta} \left[\frac{\lambda_i}{\theta + \lambda_i}\right]^{y_i} \tag{6}$$

where:

N = total number of roadway segments in the sample;
Γ = gamma function; and,
θ = $1/\alpha$.

To apply the negative binomial regression models estimated in this study, the following functional form should be used:

$$\lambda_i = e^{\beta_0} \times L \times AADT^{\beta_1} \times e^{(\beta_2 X_2 + \ldots + \beta_n X_n)} \tag{7}$$

where:

λ_i = expected number of crashes on roadway segment *i*;
e = exponential function;
β_0 = regression coefficient for constant;
L = roadway segment length (miles);
$AADT$ = average annual daily traffic (veh/day);
β_1 = regression coefficient for AADT;
$\beta_2, \ldots, \beta_n$ = regression coefficients for explanatory variables, $i = 2, \ldots, n$; and,
$X_2, \ldots, X_n$ = vector of geometric design, traffic volume, and other site-specific data.

The elasticity of each independent variable included in the model is also computed to help interpret the results of the roadway segment SPFs. The elasticities provide a measure of responsiveness of one variable to a change in another. For the continuous explanatory variables considered in this study (e.g., AADT), the elasticity is interpreted as the percent change in the expected roadway segment crash frequency given a one percent change in that continuous variable. In general, the elasticity of the expected crash frequency for continuous explanatory variable ‘*k*’ on roadway segment ‘*i*’ during time period ‘*j*’ is defined as:

$$E_{x_{ijk}}^{\lambda_{ij}} = \frac{\partial \lambda_{ij}}{\partial x_{ijk}} \times \frac{x_{ijk}}{\lambda_{ij}} \tag{8}$$

Equation 5 reduces to the following expressions for the log-log (Equation 9) and log-linear (Equation 10) functional forms, respectively. These represent the two types of functional forms considered here. The first represents the relationship modeled between expected crash frequency and the AADT variable and the second represents the relationship modeled between expected crash frequency and all other continuous variables in the roadway segment SPFs.

$$E_{x_{ijk}}^{\lambda_{ij}} = \beta_k \tag{9}$$

$$E_{x_{ijk}}^{\lambda_{ij}} = \beta_k x_{ijk} \tag{10}$$

The elasticity for indicator variables (e.g., presence of passing zones), termed *pseudo-elasticity* by Lee and Mannering (2002), is the percent change in expected crash frequency given a change in the value of the indicator variable from zero to unity. In general, the elasticity of the expected crash frequency for indicator variable ‘*k*’ on roadway segment ‘*i*’ during time period ‘*j*’ is defined as:

$$E_{x_{ijk}}^{\lambda_{ij}} = \exp(\beta_k) - 1 \tag{11}$$

Data Summary

There were 21,340 unique roadway segments included in the data analysis file. Because there were eight years of crash data available for each roadway segment (2005 to 2012), the analysis database consisted of 170,720 observations. Table 1 provides summary statistics of the segment-level data for total crashes, fatal, injury, and PDO crashes, traffic volume, and the roadway and roadside characteristics included in the analysis database.

As shown in Table 1, there are more injury and property damage only (PDO) crashes per segment than fatal crashes per segment. The categorical variables are shown in the lower panel of Table 1. The majority of roadway segments have a roadside hazard rating (RHR) or 4, 5, or 6. Fewer than 2 percent of roadway segments have curve warning, intersection warning, or “aggressive driving dots” traffic control devices.

Table 1. Crash, Traffic Volume, and Site Characteristic Data Summary

Variables	Mean	Standard Deviation	Minimum	Maximum
Total crashes per year	0.667	1.144	0	23
Total fatal crashes per year	0.015	0.123	0	3
Total injury crashes per year	0.347	0.724	0	13
Total property-damage only (PDO) crashes per year	0.306	0.672	0	13
Average annual daily traffic (veh/day)	3282	2933	74	28,674
Segment length (miles)	0.474	0.129	0.003	1.476
Posted speed limit (mph)	47.421	7.650	15	55
Left paved shoulder width (feet)	3.002	2.305	0	22
Right paved shoulder width (feet)	3.048	2.304	0	19
Access density (access points and intersections per mile)	16.300	14.307	0	330
Horizontal curve density (curves per mile)	2.299	2.506	0	42.581
Degree of curve per mile	19.100	44.178	0	1263.478
Length of curve per mile	1004.945	1237.694	0	29,256.37

Categorical Variables	Category	Proportion
Roadside hazard rating (1 to 7)	1	0.1
	2	0.5
	3	5.1
	4	21.6
	5	53.1
	6	19.4
	7	0.2
Presence of a passing zone	Yes	28.4
	No	71.6
Presence of centerline rumble strips	Yes	21.0
	No	79.0
Presence of shoulder rumble strips	Yes	8.1
	No	91.9
Presence of curve warning pavement marking	Yes	1.3
	No	98.7
Presence of intersection warning pavement marking	Yes	0.5
	No	99.5
Presence of “aggressive driving dots”	Yes	0.1
	No	99.9

Safety Performance Functions

Two SPFs were developed for two-lane rural roadway segments: one for total crash frequency, and one for the frequency of fatal and injury crashes. Each of the independent variables shown in Table 1 was entered into the preliminary models and their respective signs and statistical significance were assessed. Those variables with the expected sign that were either significant (p-value $\leq$ 0.05) or marginally significant (p-value < 0.3) were retained in the models. All SPFs were estimated in a form consistent with equation (4) above.

Note that several variables included in the Highway Safety Manual's SPFs for two-lane rural roads were excluded from consideration in the SPFs developed for two-lane rural roads in Pennsylvania due to lack of data availability, little variation in data across individual roadway segments, limited confidence in data quality or lack of application within Pennsylvania. These variables include vertical grade, presence of vertical curvature, lane and shoulder width, shoulder type, the presence of lighting and the presence of automated speed enforcement. Furthermore, the preliminary models revealed that some variables were more appropriately treated in a form that differs from the HSM models. For example, the preliminary models revealed that roadside hazard rating could be combined using groups with roadside hazard ratings of 1-3, 4-5, and 6-7, since the safety performance of roadway segments were the same within each of these groups.

Tables 2 and 3 show the results of the SPF estimation. Each table includes the regression coefficients, standard errors, and t-statistics for the independent variables included in the total and fatal and injury crash models, respectively.

Table 2. Total Crash Frequency Safety Performance Function For Segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-5.934	0.042	-142.71	<0.001
Natural logarithm of AADT	0.754	0.005	161.44	<0.001
Roadside hazard rating 6 or 7 (1 if RHR is 6 or 7; 0 otherwise)	0.101	0.018	5.67	<0.001
Roadside hazard rating 4 or 5 (1 if RHR is 4 or 5; 0 otherwise)	0.091	0.016	5.71	<0.001
Presence of a passing zone (1 if present; 0 otherwise)	-0.239	0.009	-27.56	<0.001
Presence of shoulder rumble strips (1 if present; 0 otherwise)	-0.188	0.013	-14.19	<0.001
Access density	0.008	0.0003	31.36	<0.001
Horizontal curve density	0.030	0.002	14.81	<0.001
Degree of curve per mile	0.002	0.0001	17.16	<0.001
Overdispersion parameter = 0.514 Pseudo R^2 = 0.0874 Log-likelihood at convergence = -174,406.04				

The statistical model outputs in Table 2 are integrated with the functional form of the SPF presented in Equation 7 as follows:

$$N_{cr,pr} = Length \times AADT^{0.754} \times e^{-5.934} \times e^{0.101 RHR6,7} \times e^{0.091 RHR4,5} \times e^{-0.239 PZ} \times e^{-0.188 SRS} \times e^{0.008 AD} \times e^{0.030 HCD} \times e^{0.002 DCPM}$$

where:

$N_{cr,pr}$	= predicted total crash frequency on the segment (crashes/year);
Length	= length of segment (miles);
AADT	= annual average daily traffic on the segment (veh/day);
RHR6,7	= roadside hazard rating on the segment of 6 or 7 (1 if RHR is 6 or 7; 0 otherwise);
RHR4,5	= roadside hazard rating on the segment of 4 or 5 (1 if RHR is 4 or 5; 0 otherwise);
PZ	= presence of a passing zone in the segment (1 if present; 0 otherwise);
SRS	= presence of shoulder rumble strips in the segment (1 If present; 0 otherwise);
AD	= access density in the segment, total driveways and intersections per mile of segment length (Access Points/Mile);
HCD	= horizontal curve density in the segment, number of curves in the segment per mile (Hor. Curves/Mile); and,
DCPM	= total degree of curvature per mile in the segment, the sum of degree of curvature for all curves in the segment divided by segment length in miles (Degrees/100 ft/Mile).

The same basic procedure can be repeated for any of the SPFs presented in this report to convert the SPFs from the tabular form to the equation form. More details about the SPF equations, included how these SPFs can be reduced into a "short-form" more consistent with the HSM methodology, are provided in Appendix C of this report.

The results presented in Table 2 show that the expected total crash frequency is positively correlated with traffic volume, roadside hazard ratings of 4 or higher, access density, horizontal curve density, and the degree of curvature per mile. The expected total crash frequency is negatively correlated with the presence of a passing zone and the presence of shoulder rumble strips. A more detailed interpretation of these results is provided in the discussion of the elasticities and pseudo-elasticities for each independent variable in Table 4.

Table 3. Fatal and Injury Crash Frequency Safety Performance Function for Segments

Variable	Coefficient	Standard Error	t-statistic	p-value
Constant	-6.363	0.054	-118.91	<0.001
Natural logarithm of AADT	0.735	0.006	122.29	<0.001
Roadside hazard rating 6 or 7 (1 if RHR is 6 or 7; 0 otherwise)	0.051	0.023	2.26	0.024
Roadside hazard rating 4 or 5 (1 if RHR is 4 or 5; 0 otherwise)	0.055	0.020	2.68	0.007
Presence of a passing zone (1 if present; 0 otherwise)	-0.232	0.011	-20.78	<0.001
Presence of shoulder rumble strips (1 if present; 0 otherwise)	-0.184	0.017	-10.81	<0.001
Access density	0.008	0.0003	26.43	<0.001
Horizontal curve density	0.031	0.003	12.13	<0.001
Degree of curve per mile	0.002	0.0001	12.00	<0.001
Overdispersion parameter = 0.624 Pseudo R^2 = 0.0749 Log-likelihood at convergence = -124,096.28				

The results presented in Table 3 show that the expected fatal and injury crash frequency is positively correlated with traffic volume, roadside hazard ratings of 4 or higher, access density, horizontal curve density, and the degree of curvature per mile. The expected fatal and injury crash frequency is negatively correlated with the presence of a passing zone and the presence of shoulder rumble strips. A more detailed interpretation of these results is provided in the discussion of the elasticities and pseudo-elasticities for each independent variable in Table 4.

Table 4 shows the elasticities and pseudo-elasticities for the independent variables in Tables 2 and 3. Note that the elasticities for continuous variables other than AADT (such as access density, horizontal curve density and degree of curve per mile) are all a function of the value at which they are assessed. The elasticities presented in Table 4 are all provided at the mean values of these variables as provided in Table 1.

Table 4. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models

Variable	Total Crashes	Fatal and Injury Crashes
Natural logarithm of AADT	0.754	0.735
Roadside hazard rating 6 or 7 (1 if RHR is 6 or 7; 0 otherwise)	10.6	5.27
Roadside hazard rating 4 or 5 (1 if RHR is 4 or 5; 0 otherwise)	9.57	5.61
Presence of a passing zone (1 if present; 0 otherwise)	-21.3	-20.7
Presence of shoulder rumble strips (1 if present; 0 otherwise)	-17.1	-16.8
Access density	0.130	0.138
Horizontal curve density	0.069	0.071
Degree of curve per mile	0.035	0.031

The elasticities provide the percent change in expected crash frequency when the independent variable is increased by one percent (for continuous variables such as AADT, access density, horizontal curve density and degree of curve per mile) or changed from zero to one (for indicator variables such as roadside hazard rating group, presence of passing zone or shoulder rumble strips). As expected, there is a positive relationship between traffic volume and crash frequency: a one percent change in AADT will increase the expected total crash frequency by 0.754 percent and fatal and injury crash frequency by 0.735 percent, holding all other variables constant. At the average value provided in the dataset, an increase in access point density by one percent will increase the expected total crash frequency (0.130 percent) slightly less than the expected fatal and injury crash frequency (0.138 percent), although both magnitudes are about the same and relatively small. The increase in both total crash frequency and fatal and injury crash frequency is the same for a one percent increase in horizontal curve density (about 0.070 percent) and a one percent increase in degree of curvature per mile (about 0.033 percent) at the mean values observed.

As expected, segments with roadside hazard ratings greater than 3 are associated with significantly higher crash frequencies than those with poor roadside hazard ratings. For the expected total crash frequency, a roadside hazard rating of 4 or 5 is associated with a 9.57 percent increase over the base condition (RHR of 1 to 3) and a roadside hazard rating of 6 or 7 is associated with a 10.6 percent increase over the base condition. For the expected fatal and injury crash frequency, a roadside hazard rating of 4 or 5 is associated with a 5.27 percent increase over the base condition and a roadside hazard rating of 6 or 7 is associated with a 5.61 percent increase over the base condition. The presence of passing zones and shoulder rumble strips are both associated with lower expected crash frequencies relative to the base condition of no passing zones or no shoulder rumble strips, respectively. Passing zones will decrease both expected total and fatal and injury crash frequency by about 21 percent while shoulder rumble strips will decrease both expected total and fatal and injury crash frequency by about 17 percent, holding all other variables in the model constant.

Summary of Findings

This section of the report estimated statistical models of total and fatal and injury crash frequency for roadway segments of state-owned, two-lane rural highway segments in Pennsylvania. This modeling effort found that both crash frequency types were a function of traffic volumes (measured in AADT), roadside hazard rating, presence of shoulder rumble strips and passing zones, densities of access points and horizontal curves, and the degree of horizontal curvature within the roadway segment. As expected, the models predict significantly lower fatal and injury crash frequencies than total crash frequencies. However, the elasticities suggest that almost all independent variables impact total and fatal and injury crash frequency by the same magnitude. The lone exception is roadside hazard rating, for which the impact is about 85% larger for total crash frequency than fatal and injury crash frequency.

Several explanatory variables included in Table 1 were omitted from the models either because they were not statistically insignificant or were found to be unreliable. Examples of the latter include roadway width and speed limit. In many cases, roadway widths provided in the RMS database were unrealistically large (greater than 40 feet) or small (less than 20 feet) for two-lane rural roadways. Similarly, speeds limits as low as 15 mph were recorded in the RMS database, which are typically indicative of warning speeds and not regulatory speeds. More reliable records for these variables should be considered for future modeling efforts.

INTERSECTION SAFETY PERFORMANCE FUNCTIONS

This section of the report describes the SPFs developed for rural two-lane highway intersections in Pennsylvania. Statistical models for total crash frequency and frequency of different levels of crash injury severity were estimated for intersections formed by three-digit state-owned roads on the rural two-lane highways. Included in this section of the report are the statistical modeling methodology, data summary, analysis results, and interpretation of the statistical modeling output. The data elements and structures used to construct the modeling data files were described earlier in this report.

Statistical models are reported for all intersections of two state-owned two-lane rural roads with the following intersection forms:

- 4-leg intersections with signal control
- 3-leg intersections with signal control
- 4-leg intersections with all-way stop control
- 4-leg intersections with minor-street stop control
- 3-leg intersections with minor-street stop control

It should be noted that PennDOT's linear referencing system was used to derive the "influence" area intersection for crash frequency modeling purposes. Many recent safety evaluation studies defined intersection-related crashes as those reported within 250-feet of the point where the two intersecting roadway alignments cross (e.g., Bauer and Harwood, 1996; Harwood et al., 2003; Mitra and Washington, 2012; Wang and Abdel-Aty, 2006). The same influence area is assumed here for each of the state-owned two-lane rural road intersections identified using the RMS data.

Statistical Modeling Methodology

As noted in the roadway segment SPF section of this report, several cross-sectional modeling approaches were considered, but negative binomial regression was used in an effort to be consistent with the first edition of the HSM. In this section of the report, the expected number of intersection crashes per year was modeled as a function of several explanatory variables. Several examples of intersection SPF development using negative binomial regression can be found in the published traffic safety literature (e.g., Poch and Mannering 1996; Bauer and Harwood 1996; Washington et al. 2005). Similar to the crash frequency models for segments, this modeling approach accounts for the overdispersion that exists in the crash data. The general functional form of the negative binomial regression model, the mean-variance relationship, and the maximum likelihood function, are shown in Equations (12) through (14). The difference between the roadway segment analysis and the intersection-level analysis is the model specification, which is shown in Equation (12) below for intersections:

$$\lambda_i = e^{\beta_0} \times AADT_{major}^{\beta_1} \times AADT_{\mathrm{min}or}^{\beta_2} \times e^{(\beta_3 X_3 + \ldots + \beta_n X_n)} \qquad (12)$$

where:

λ_i	= expected number of crashes at intersection *i*;
e	= exponential function;
β_0	= regression coefficient for constant;
$AADT_{major}$	= average annual daily traffic (veh/day) for major roadway;
$AADT_{minor}$	= average annual daily traffic (veh/day) for minor roadway;
β_1, β_2	= regression coefficients for major and minor road AADT, respectively,
β_3, …, β_n	= regression coefficients for explanatory variables, *i* = 3, …, *n*; and,
X_3, …, X_n	= vector of geometric design and other site-specific data.

When interpreting the intersection SPFs, the elasticity and pseudo-elasticity for the independent variables in the model were computed using Equations (8) through (11).

Data Summary

There were 683 unique intersections included in the data analysis file. The distribution of these intersections based on the type of the intersection was:

- 4-leg signalized - 105 of this form
- 3-leg signalized - 45 of this form
- 4-leg all-way stop-control - 33 of this form
- 4-leg two-way stop-control - 86 of this form
- 3-leg two-way stop-control - 414 of this form

Two-way stop control was provided on the minor approach(es) of the 3- and 4-leg intersections. Because there were eight (8) years of crash data for each intersection, the analysis database consisted of 5,464 unique annual intersection observations.

Tables 5 and 6 provide summary statistics for the total crashes and total fatal and injury crashes recorded for each intersection type. As expected, the total crash frequency is higher than the fatal and injury crash frequency. The signalized intersection forms have the highest mean frequency of severe (fatal and injury) crashes.

Table 5. Summary Statistics for Total Crash Frequency by Intersection Type

Intersection Type	Number of observations	Mean	Standard Deviation	Minimum	Maximum
4-leg, signalized	840	3.136	3.213	0	20
3-leg, signalized	360	1.922	2.559	0	15
4-leg, all-way stop	264	1.97	2.538	0	12
4-leg, two-way stop	688	1.637	2.312	0	15
3-leg, two-way stop	3312	1.383	2.023	0	16
ALL	5464	1.748	2.421	0	20

Table 6. Summary Statistics for Fatal and Injury Crash Frequency by Intersection Type

Intersection Type	Mean	Standard Deviation	Minimum	Maximum
4-leg, signalized	1.677	2.104	0	15
3-leg, signalized	1.203	1.831	0	13
4-leg, all-way stop	1.023	1.594	0	8
4-leg, two-way stop	0.920	1.663	0	11
3-leg, two-way stop	0.766	1.348	0	12
ALL	0.957	1.597	0	15

Tables 7 through 11 present summary statistics for the independent variables considered in the SPF development broken down by the five intersection forms included in this report. The signalized intersections and the 3-leg, two-way stop-controlled intersection forms have the highest traffic volumes. The paved width includes the through lanes, turning lanes, and paved shoulder widths on each of the major and minor approaches; therefore, these widths vary widely within each intersection form, and when compared across the different intersection forms. The number of turn-lanes is generally higher at signalized intersections when compared to stop-controlled intersections. The posted speed limits vary considerably for all intersection types.

Table 7. Summary Statistics for 4-leg Signalized Intersections

Continuous Variable	Mean	Standard Deviation	Minimum	Maximum
Total Crashes per Year	3.136	3.213	0	20
Total Fatal and Injury Crashes per Year	1.677	2.104	0	15
Major Road AADT (veh/day)	7399	4102	793	23,375
Minor Road AADT (veh/day)	3858	2432	285	13,699
Left Shoulder Total Width on Major Road (feet)	3.682	2.885	0	13
Right Shoulder Total Width on Major Road (feet)	3.637	2.885	0	10
Paved Width on Major Road (feet)	27.988	7.872	20	54
Posted Speed Limit on Major Road (mph)	40.851	9.640	25	55
Left Shoulder Total Width on Minor Road (feet)	3.061	2.407	0	10
Right Shoulder Total Width on Minor Road (feet)	3.087	2.489	0	10
Paved Width on Minor Road (feet)	24.136	5.185	19	54
Posted Speed Limit on Minor Road (mph)	39.244	9.476	25	55
Intersection Skew Angle (degree)	76.714	15.560	15	90

Categorical Variable	Description	Proportion
Presence of exclusive left-turn lanes on major road approach	None	70.48
	Present on one approach	22.86
	Present on both approaches	6.67
Presence of exclusive right-turn lanes on major road approach	None	84.76
	Present on one approach	14.29
	Present on both approaches	0.95
Presence of pedestrian crosswalk on major road approach	None	74.52
	Present on one approach	15.00
	Present on both approaches	10.48
Presence of intersection warning on major road approach	None	97.86
	Present	2.14
Presence of exclusive left-turn lane on minor road approach	None	78.10
	Present on one approach	16.19
	Present on both approaches	5.71
Presence of exclusive right-turn lane on minor road approach	None	86.67
	Present on one approach	10.48
	Present on both approaches	2.86
Presence of pedestrian crosswalk on major road approach	None	71.19
	Present on one approach	18.33
	Present on both approaches	10.48
Presence of intersection warning on major road approach	None	95.48
	Present	4.52

Table 8. Summary Statistics for 3-leg Signalized Intersections

Continuous Variable	Mean	Standard Deviation	Minimum	Maximum
Total Crashes per Year	1.922	2.558	0	15
Total Fatal and Injury Crash per Year	1.203	1.831	0	13
Major Road AADT (veh/day)	6710	3815	913	17,265
Minor Road AADT (veh/day)	4127	2819	324	12,501
Left Shoulder Total Width on Major Road (feet)	2.769	2.960	0	10
Right Shoulder Total Width on Major Road (feet)	2.858	3.141	0	10
Paved Width on Major Road (feet)	28.928	7.041	20	50
Posted Speed Limit on Major Road (mph)	38.722	11.072	20	55
Left Shoulder Total Width on Minor Road (feet)	2.297	1.992	0	8
Right Shoulder Total Width on Minor Road (feet)	2.386	2.011	0	8
Paved Width on Minor Road (feet)	24.739	5.139	20	42
Posted Speed Limit on Minor Road (mph)	37.833	9.005	25	55
Intersection Skew Angle (degree)	76.000	17.203	20	90

Categorical Variable	Description	Proportion
Presence of exclusive left-turn lane on major road approach	None	71.67
	Present	28.33
Presence of exclusive right-turn lane on major road approach	None	93.61
	Present	6.39
Presence of pedestrian crosswalk on major road approach	None	76.11
	Present on one approach	19.44
	Present on both approaches	4.44
Presence of exclusive left-turn lanes on minor road	None	95
	Present	5
Presence of exclusive right-turn lanes on minor road	None	93.06
	Present	6.94
Presence of pedestrian crosswalk on minor road	None	77.22
	Present on one approach	18.33
	Present on both approaches	4.44

Table 9. Summary Statistics for 4-leg All-way Stop-controlled Intersections

Continuous Variable	Mean	Standard Deviation	Minimum	Maximum
Total Crashes per Year	1.970	2.538	0	12
Total Fatal and Injury Crash per Year	1.023	1.594	0	8
Major Road AADT (veh/day)	3763	2745	740	11,351
Minor Road AADT (veh/day)	1973	1356	317	5959
Left Shoulder Total Width on Major Road (feet)	4.254	2.473	0	10
Right Shoulder Total Width on Major Road (feet)	4.432	2.544	0	10
Paved Width on Major Road (feet)	22.659	3.268	20	35
Posted Speed Limit on Major Road (mph)	45.436	9.089	25	55
Left Shoulder Total Width on Minor Road (feet)	2.928	1.845	0	8
Right Shoulder Total Width on Minor Road (feet)	2.932	1.865	0	8
Paved Width on Minor Road (feet)	21.098	2.325	18	32
Posted Speed Limit on Minor Road (mph)	42.746	7.107	25	55
Intersection Skew Angle (degrees)	67.727	17.314	10	90
Categorical Variable	**Description**		**Proportion**	
Presence of exclusive left-turn lane on major road approach	None		96.97	
	Present on both approaches		3.03	
Presence of exclusive right-turn lane on major road approach	None		90.91	
	Present on one approach		6.06	
	Present on both approaches		3.03	
Presence of pedestrian crosswalk on major road approach	None		96.97	
	Present on one approach		3.03	
Presence of intersection warning on major road	None		96.97	
	Present		3.03	
Presence of exclusive left-turn lane on minor road approach	None		96.97	
	Present on one approach		3.03	
Presence of exclusive right-turn lane on minor road approach	None		96.97	
	Present on both approaches		3.03	
Presence of pedestrian crosswalk on minor road approach	None		96.97	
	Present on one approach		3.03	
Presence of intersection warning on minor road	None		90.91	
	Present		9.09	

Table 10. Summary Statistics for 4-leg Two-way Stop-controlled Intersections

Continuous Variable	Mean	Standard Deviation	Minimum	Maximum
Total Crashes per Year	1.637	2.312	0	15
Total Fatal and Injury Crash per Year	0.920	1.663	0	11
Major Road AADT (veh/day)	3913	2761	312	14,387
Minor Road AADT (veh/day)	1681	1278	172	8923
Left Shoulder Total Width on Major Road (feet)	3.610	2.362	0	14
Right Shoulder Total Width on Major Road (feet)	3.750	2.537	0	14
Paved Width on Major Road (feet)	23.968	6.818	20	66
Posted Speed Limit on Major Road (mph)	43.721	8.706	25	55
Left Shoulder Total Width on Minor Road (feet)	2.797	1.833	0	8
Right Shoulder Total Width on Minor Road (feet)	2.762	1.876	0	8
Paved Width on Minor Road (feet)	21.799	3.252	18	40
Posted Speed Limit on Minor Road (mph)	41.919	8.081	25	55
Skew Angle on Major Route (degree)	72.151	18.559	15	90

Categorical Variable	Description	Proportion
Presence of exclusive left-turn lane on major approach	None	96.51
	Present on one approach	2.33
	Present on both approaches	1.16
Presence of pedestrian crosswalk on major road approach	None	96.51
	Present on one approach	3.49
Presence of intersection warning on major road approach	None	99.13
	Present	0.87
Presence of exclusive left-turn lane on minor approach	None	98.84
	Present on both approaches	1.16
Presence of exclusive right-turn lane on minor approach	None	98.84
	Present on one approach	1.16
Presence of pedestrian crosswalk on minor road approach	None	93.02
	Present on one approach	6.98
Presence of intersection warning on minor road approach	None	98.55
	Present	1.45

Table 11. Summary Statistics for 3-leg Two-way Stop-controlled Intersections

Continuous Variable	Mean	Standard Deviation	Minimum	Maximum
Total Crashes per Year	1.383	2.023	0	16
Total Fatal and Injury Crashes per Year	0.766	1.348	0	12
Major Road AADT (veh/day)	4109	2873	138	19,161
Minor Road AADT (veh/day)	1992	1734	74	14,537
Left Shoulder Total Width on Major Road (feet)	4.342	2.473	0	12
Right Shoulder Total Width on Major Road (feet)	4.356	2.449	0	11
Paved Width on Major Road (feet)	23.278	3.714	18	41
Posted Speed Limit on Major Road (mph)	46.443	8.189	15	55
Left Shoulder Total Width on Minor Road (feet)	3.201	1.939	0	12
Right Shoulder Total Width on Minor Road (feet)	3.289	2.001	0	11
Paved Width on Minor Road (feet)	21.920	3.612	16	66
Posted Speed Limit on Minor Road (mph)	44.269	8.561	20	55
Intersection Skew Angle (degree)	65.145	21.136	10	90

Categorical Variable	Description	Proportion
Presence of exclusive left-turn lane on major approach	None	94.96
	Present on one approach	5.04
Presence of exclusive right-turn lane on major approach	None	96.62
	Present on one approach	3.38
Presence of pedestrian crosswalk on major road approach	None	99.52
	Present on one approach	0.48
Presence of intersection warning on major road approach	None	99.31
	Present	0.69
Presence of exclusive left-turn lane on minor approach	None	96.11
	Present on one approach	3.89
Presence of exclusive right-turn lane on minor approach	None	95.41
	Present on one approach	4.59
Presence of pedestrian crosswalk on minor road approach	None	99.52
	Present on one approach	0.48
Presence of intersection warning on minor road approach	None	99.00
	Present	1.00

Safety Performance Functions

Two SPFs were developed for each of the five intersection types: one for total crash frequency, and one for the frequency of fatal and injury crashes. Each of the independent variables shown in Tables 7 through 11 was entered into the preliminary models and their respective signs and statistical significance were assessed. Those variables with the expected sign that were either significant (p-value $\leq$ 0.05) or marginally significant (p-value < 0.3) were retained in the models. All SPFs were estimated in a form consistent with equation (12) above.

As with the SPFs developed for roadway segments, several variables included in the Highway Safety Manual's SFPs for intersections of two-lane rural roads were excluded from consideration in the SPFs developed for Pennsylvania due to lack of data availability, little variation within the data across all sites, limited confidence in data quality or lack of application within Pennsylvania.

Tables 12 through 16 show the results of the SPF estimation. Each table includes the regression coefficients, standard errors, and t-statistics for the independent variables included in the total and fatal and injury crash models.

The results shown in Table 12 shows that the coefficient of major road AADT is larger in magnitude than the coefficient of minor road AADT for total crash frequency, indicating that the major road traffic volume affects total crash frequency more than minor road AADT at 4-leg, signalized intersections on two-lane rural highways in Pennsylvania. For fatal and injury crash frequency, the two coefficients are almost equal, which indicates that the major and minor road AADT affect fatal and injury crash frequency similarly. All coefficients for the independent variables included in the total and fatal and injury crash models are positive, indicating that a unit increase in these variables is associated with an increase in total and fatal and injury crashes at 4-leg, signalized intersections in Pennsylvania.

Table 12. Safety Performance Function for 4-leg Signalized Intersections

Variable	Coefficient	Standard Error	t-statistic
Total Crashes			
Constant	-5.353	0.552	-9.70
Logarithm of Major Road AADT	0.313	0.073	4.29
Logarithm of Minor Road AADT	0.250	0.071	3.53
Posted Speed Limit on Major Road (mph)	0.025	0.004	5.97
Posted Speed Limit on Minor Road (mph)	0.014	0.004	3.34
Presence of Exclusive Right-Turn Lane on Either Major Approach	0.216	0.092	2.35
Overdispersion Parameter	0.579	0.052	-
Number of Observations = 840 Log-likelihood = -1832.34 Pseudo-R2 = 0.0455			
Fatal and Injury Crashes			
Constant	-4.960	0.715	-6.94
Logarithm of Major Road AADT	0.202	0.094	2.15
Logarithm of Minor Road AADT	0.209	0.091	2.3
Posted Speed Limit on Major Road (mph)	0.028	0.005	5.21
Posted Speed Limit on Minor Road (mph)	0.018	0.006	3.21
Presence of Exclusive Right-Turn Lane on Either Major Approach	0.388	0.117	3.33
Overdispersion Parameter	0.892	0.093	-
Number of Observations = 840 Log-likelihood = -1428.93 Pseudo-R2 = 0.0370			

The results in Table 13 show that the coefficient of major road AADT is larger in magnitude than the minor road AADT, indicating that the major road traffic volume affects total and fatal and injury crash frequency more than minor road AADT at 3-leg, signalized intersections on two-lane rural highways in Pennsylvania. This finding is consistent with the findings of the HSM (AASHTO, 2010). The positive coefficients for AADT and the posted speed limit in both models suggest that an increase in each of these variables is associated with an increase in crash frequency at 3-leg, signalized intersections in Pennsylvania. The coefficients for the presence of crosswalks on the major and minor road approaches are negative in both models, which suggest that the presence of a crosswalk is associated with a decrease in crash frequency at 3-leg, signalized intersections in Pennsylvania.

Table 13. Safety Performance Function for 3-leg Signalized Intersections

Variable	Coefficient	Standard Error	t-statistic
Total Crashes			
Constant	-6.813	1.050	-6.49
Logarithm of Major Road AADT	0.451	0.185	2.44
Logarithm of Minor Road AADT	0.349	0.158	2.21
Posted Speed Limit on Major Road (mph)	0.020	0.006	3.08
Presence of a Crosswalk on Major Road Approach	-0.433	0.188	-2.31
Presence of a Crosswalk on Minor Road Approach	-0.345	0.200	-1.73
Overdispersion Parameter	0.982	0.149	-
Number of Observations = 360 Log-likelihood = -637.61 Pseudo-R2 = 0.0490			
Fatal and Injury Crashes			
Constant	-6.981	1.182	-5.90
Logarithm of Major Road AADT	0.452	0.208	2.17
Logarithm of Minor Road AADT	0.287	0.180	1.59
Posted Speed Limit on Major Road (mph)	0.026	0.007	3.47
Presence of a Crosswalk on Major Road Approach	-0.605	0.218	-2.77
Presence of a Crosswalk on Minor Road Approach	-0.413	0.235	-1.76
Overdispersion Parameter	1.114	0.205	-
Number of Observations = 360 Log-likelihood = -511.26 Pseudo-R2 = 0.0518			

The results in Table 14 show that the coefficient of major road AADT is larger in magnitude than the minor road AADT, indicating that the major road traffic volume affects total and fatal and injury crash frequency more than minor road AADT at 4-leg, all-way stop-controlled intersections on two-lane rural highways in Pennsylvania. This finding is consistent with the findings of the HSM (AASHTO, 2010). The AADT and posted speed limit variables have a positive sign suggesting that 4-leg all-way stop-controlled intersections on two-way rural highways in Pennsylvania with higher traffic volumes and higher posted speed limits on the major approach are associated with higher total and fatal and injury crash frequencies.

Table 14. Safety Performance Function for 4-leg All-way Stop-controlled Intersections

Variable	Coefficient	Standard Error	t-statistic
Total Crashes			
Constant	-5.820	1.221	-4.77
Logarithm of Major Road AADT	0.693	0.146	4.75
Logarithm of Minor Road AADT	0.087	0.169	0.52
Posted Speed Limit on Major Road (mph)	0.057	0.015	3.65
Overdispersion Parameter	1.24	0.200	-
Number of Observations = 264 Log-likelihood = -473.45 Pseudo-R2 = 0.0425			
Fatal and Injury Crashes			
Constant	-6.515	1.439	-4.53
Logarithm of Major Road AADT	0.630	0.183	3.44
Logarithm of Minor Road AADT	0.166	0.199	0.84
Posted Speed Limit on Major Road (mph)	0.046	0.0178	2.58
Overdispersion Parameter	1.547	0.311	-
Number of Observations = 264 Log-likelihood = -350.03 Pseudo-R2 = 0.0372			

The results shown in Table 15 shows that the coefficient of major road AADT is larger in magnitude than the minor road AADT, indicating that the major road traffic volume affects total and fatal and injury crash frequency more than minor road AADT at 4-leg, two-way stop-controlled intersections on two-lane rural highways in Pennsylvania. This finding is consistent with the findings of the HSM (AASHTO, 2010). The positive coefficient for skew angle suggests that 4-leg, two-way stop-controlled intersections on two-lane rural highways in Pennsylvania with larger skew angles are associated with higher total and fatal and injury crash frequencies. This particular trend is surprising, as one would intuitively suspect that intersections with smaller skew angles would present more challenges to drivers judging opposing traffic on the uncontrolled major road. However, the majority of intersections had large skew angles (i.e., near 90-degree angles) and drivers might behave more cautiously when approaching intersections with lower skew angles.

Table 15. Safety Performance Function for 4-leg Two-way Stop-controlled Intersections

Variable	Coefficient	Standard Error	t-statistic
Total Crashes			
Constant	-6.359	0.774	-8.22
Logarithm of Major Road AADT	0.528	0.090	5.84
Logarithm of Minor Road AADT	0.275	0.078	3.51
Intersection Skew Angle (degree)	0.007	0.003	2.34
Overdispersion Parameter	1.348	0.138	-
Number of Observations = 688 Log-likelihood = -1150.67 Pseudo R2 = 0.0322			
Fatal and Injury Crashes			
Constant	-6.156	1.027	-6.00
Logarithm of Major Road AADT	0.512	0.123	4.16
Logarithm of Minor Road AADT	0.176	0.104	1.70
Intersection Skew Angle (degree)	0.008	0.004	1.98
Overdispersion Parameter	2.597	0.301	-
Number of Observations = 688 Log-likelihood = -854.78 Pseudo R2 = 0.0199			

The results in Table 16 show that the coefficient of major road AADT is larger in magnitude than the minor road AADT, indicating that the major road traffic volume affects total and fatal and injury crash frequency more than minor road AADT at 3-leg, two-way stop-controlled intersections on two-lane rural highways in Pennsylvania. This finding is consistent with the findings of the HSM (AASHTO, 2010). The coefficients for exclusive left-turn lanes and exclusive right-turn lanes on the major approach have opposite signs, suggesting somewhat offsetting effects. However, the magnitude of the sign for exclusive right-turn lanes is about twice that of exclusive left-turn lanes, indicating that the presence of an exclusive right-turn lane more significantly affects total and fatal and injury crash frequency at 3-leg, two-way stop-controlled intersections on two-lane rural highways in Pennsylvania.

Table 16. Safety Performance Function for 3-leg Two-way Stop-controlled Intersections

Variable	Coefficient	Standard Error	t-statistic
Total Crashes			
Constant	-6.337	0.311	-20.36
Logarithm of Major Road AADT	0.479	0.043	11.24
Logarithm of Minor Road AADT	0.362	0.035	10.45
Presence of Exclusive Left-Turn Lane on Major Approach	-0.330	0.113	-2.93
Presence of Exclusive Right-Turn Lane on Major Approach	0.507	0.128	3.96
Overdispersion Parameter	1.117	0.060	-
Number of Observations = 3312 Log-likelihood = -5055.11 Pseudo-R2 = 0.0485			
Fatal and Injury Crashes			
Constant	-6.457	0.402	-16.07
Logarithm of Major Road AADT	0.439	0.056	7.86
Logarithm of Minor Road AADT	0.343	0.45	7.57
Presence of Exclusive Left-Turn Lane on Major Approach	-0.267	.0144	-1.85
Presence of Exclusive Right-Turn Lane on Major Approach	0.560	0.163	3.44
Overdispersion Parameter	1.81	0.115	-
Number of Observations = 3312 Log-likelihood = -3756.41 Pseudo-R2 = 0.0366			

Tables 17 to 21 show the elasticities and pseudo-elasticities for the independent variables in Tables 12 to 16. Note that the elasticities for any continuous variables other than AADTs (e.g., posted speed limits or skew angles) are all provided at their average values as provided in Table 7 and Table 11. The elasticities for the AADT variables all hold for the entire range of AADTs observed.

Table 17. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models for 4-leg Signalized Intersections

Variable	Total Crashes	Fatal and Injury Crashes
Logarithm of Major Road AADT	0.313	0.202
Logarithm of Minor Road AADT	0.250	0.209
Posted Speed Limit on Major Road (mph)	1.02	1.14
Posted Speed Limit on Minor Road (mph)	0.549	0.706
Presence of Exclusive Right-Turn Lane on Either Major Approach	24.1	47.4

The elasticities suggest that a one percent increase in major road AADT is associated with a 0.313 percent increase in total crash frequency and a 0.202 percent increase in fatal and injury crash frequency at 4-leg signalized intersections on two-lane rural roads in Pennsylvania. Minor road AADT has a less pronounced effect, as a one percent increase is only associated with a 0.250 percent increase in total crash frequency and 0.209 increase in fatal and injury crash frequency. A one percent increase in the posted speed limit on the major road has a larger impact on total and fatal and injury crash frequency (1.02 and 1.14 percent, respectively) than a one percent increase in the posted speed limit on the minor road (0.549 percent and 0.706 percent, respectively) when both are held constant at their mean values. The presence of an exclusive left-turn lane on either major road approach is associated with an increase in total crash frequency of 24.1 percent and total and injury crash frequency of 47.4 percent. Note that all other elasticity tables can be interpreted similarly.

Table 18. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models for 3-leg Signalized Intersections

Variable	Total Crashes	Fatal and Injury Crashes
Logarithm of Major Road AADT	0.451	0.452
Logarithm of Minor Road AADT	0.349	0.287
Posted Speed Limit on Major Road (mph)	0.774	1.01
Presence of a Crosswalk on Major Road Approach	-35.1	-45.4
Presence of a Crosswalk on Minor Road Approach	-29.2	-33.8

Table 19. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models for 4-leg All-way Stop-controlled Intersections

Variable	Total Crashes	Fatal and Injury Crashes
Logarithm of Major Road AADT	0.693	0.630
Logarithm of Minor Road AADT	0.087	0.166
Posted Speed Limit on Major Road (mph)	2.59	2.09

Table 20. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models for 4-leg Two-way Stop-controlled Intersections

Variable	Total Crashes	Fatal and Injury Crashes
Logarithm of Major Road AADT	0.528	0.512
Logarithm of Minor Road AADT	0.275	0.176
Skew Angle on Major Route (degree)	0.505	0.577

Table 21. Elasticities for Independent Variables in Total and Fatal and Injury Crash Models for 3-leg Two-way Stop-controlled Intersections

Variable	Total Crashes	Fatal and Injury Crashes
Logarithm of Major Road AADT	0.479	0.439
Logarithm of Minor Road AADT	0.362	0.343
Presence of Exclusive Left-Turn Lane on Major Approach	-28.1	-23.4
Presence of Exclusive Right-Turn Lane on Major Approach	66.0	75.1

Summary

This section estimated statistical models of total and fatal and injury crash frequency for five intersection types on two-lane rural highways in Pennsylvania. The major road AADT coefficient was larger than the minor road AADT in most models, which is consistent with the *Highway Safety Manual* SPFs. The other independent variables included in the models are generally consistent with engineering intuition. The elasticities in Tables 17 through 21 show that the total and fatal and injury crash frequency increases as the posted speed limit on the major or minor road increases. These findings are consistent with several models reported by Washington et al., (2005).

The presence of an exclusive left-turn lane on the major road approach was consistently found to be associated with lower expected crash frequencies, while the presence of a right-turn lane on the major road approach was found to be associated with an increase in expected crash frequency, when included in the SPFs. The left-turn lane finding is consistent with the *Highway Safety Manual* crash modification factor for exclusive left-turn lanes; however, the right-turn lane finding is opposite of the crash modification factor reported in the *Highway Safety Manual*. It should be noted that Washington et al., (2005) found the sign of the exclusive right-turn lane indicator variable to be inconsistent across various intersection SPFs. Future consideration of the positive relationship between right-turn presence on major road approaches and crash frequency is recommended.

The presence of pedestrian crosswalks on the major and minor road approaches was associated with fewer expected crashes when included in the SPF model specification. This finding is consistent with engineering intuition and suggests that driver travel more cautiously when pedestrian crossings are present at an intersection in rural areas.

CASE STUDIES

Two realistic case studies were developed to demonstrate the application of the SPFs for segments and intersections that were developed in the previous two sections, respectively. These case studies all follow the format of the example case studies in the HSM for consistency with that guide. The reader is encouraged to refer to the HSM for more specific details on each of the individual steps.

Case study 1 – Estimating crash frequencies for an existing roadway segment

The site/facility

The section of SR 322 shown in Figure 1 below.

The question

What is the predicted average crash frequency of the roadway segment for the year 2013 when considering the previous crash history?

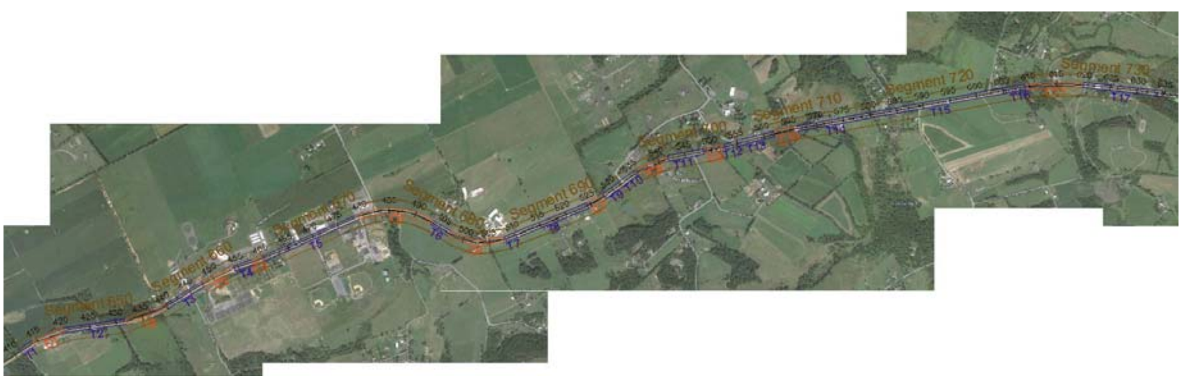

Figure 1. Section of SR 322 considered.

The facts

The section of roadway covers a length of approximately 4.2 miles and contains both curve and tangent sections. A detailed description of the geometric and other characteristics of this roadway section relevant to the safety performance prediction is provided in Table 22 below. This information has been provided for each of the predefined roadway segments based on the PennDOT Roadway Management System (RMS) database.

Table 22. Geometric and Other Characteristics of Study Area

Segment Number	Length [mi]	Roadside Hazard Rating (RHR)	Passing Zone (PZ)	Shoulder Rumble Strips (SRS)	Access Density (AD) [access points/mi]	Horizontal Curve Density (HCD) [curves per mile)	Deg. Of Curve per Mile (DCPM) [degrees/ 100 feet/ mile)
650	0.4477	4	0	1	8.934	2.234	7.817
660	0.4712	4	0	1	16.977	4.244	10.611
670	0.4261	4	0	1	30.507	2.347	2.347
680	0.5314	4	0	1	16.935	3.763	16.935
690	0.4059	4	0	1	7.392	2.464	9.855
700	0.4367	4	0	1	6.869	4.579	11.447
710	0.4813	4	0	1	14.545	2.078	2.078
720	0.5053	4	0	1	17.811	0.000	0.000
730	0.5259	4	0	1	13.309	1.901	2.852

The first column of Table 22 provides the segment numbers that make up this particular section of SR 322; these segment boundaries are illustrated on Figure 1. The second column provides the length of each segment in miles. The third column provides the roadside hazard rating (RHR) of each segment as defined in Zeeger et al (1986). The roadside hazard rating is a qualitative characterization of the crash potential for roadside designs on two-lane highways. The next column denotes the presence of passing zones (PZ) somewhere within each roadway segment. A binary value is used to represent this information: a value of 0 represents no passing zones while a value of 1 represents that at least one passing zone is present. The following column denotes the presence of shoulder rumble strips (SRS) somewhere within each roadway segment. This is also provided by a binary variable: a value of 0 represents no shoulder rumble strips while a value of 1 represents that shoulder rumble strips are present for at least some portion of the segment. The next column provides the access point density (AD) within the roadway segment in units of access points per mile. Access points are defined as state-owned and non-stated owned intersections and driveways that have access to the roadway segment. The following column presents the horizontal curve density (HCD) within the roadway segment in units of number of horizontal curves per mile. The final column provides the total degree of curvature per mile in the segment, measured in units of degrees per 100 feet per mile. This is obtained by summing the degree of curvature for each individual curve within a segment and dividing this by the total length of the segment in miles. Note that if a single curve penetrates multiple segments, the curve is attributed to the segment that contains the majority of the curve length.

The length of each segment is provided directly in the PennDOT RMS database. The roadside hazard rating, passing zones, shoulder rumble strips and access density variables were collected using the PennDOT online video photolog system as previously described in this report. This information has been collected for all state-owned, two-lane rural roads within Pennsylvania and the data has been provided to PennDOT for use in safety applications. The curve information (horizontal curve density and degree of curvature per mile) was collected using satellite imagery through the Google Earth tool, as previous described. This information has been collected for three-digit and lower state owned, two-lane rural roads within Pennsylvania and the data has been provided to PennDOT for use in safety applications.

Table 23 also provides estimates of historical traffic volume data for each of the segments identified in Table 22. This data is maintained in and available from PennDOTs RMS database.

Table 23. Traffic Volumes For Road Segments in Study Area

Segment	Average Annual Daily Traffic (AADT) [veh/day]								
	2005	2006	2007	2008	2009	2010	2011	2012	2013
650	11533	11648	11550	11550	11550	11550	11550	11550	11171
660	11533	11648	11550	11550	11550	11550	11550	11550	11171
670	11533	11648	11550	11550	11550	11550	11550	11550	11171
680	11533	11648	11550	11550	11550	11550	11550	11550	11171
690	11533	11648	11550	11550	11550	11550	11550	11550	11171
700	11533	11648	11550	11550	11550	11550	11550	11550	11171
710	11533	11648	11550	11550	11550	11550	11550	11550	11171
720	11533	11648	11550	11550	11550	11550	11550	11550	11171
730	11533	11648	11550	11550	11550	11550	11550	11550	11171

Historical crash frequencies for total crashes and fatal and injury crashes are provided in Table 24 and Table 25 respectively. This crash data was obtained from the PennDOT electronic crash history database.

Table 24. Total Crash Frequencies for Study Area

Segment	2005	2006	2007	2008	2009	2010	2011	2012	Mean
650	1	2	1	1	0	2	2	0	1.125
660	4	0	2	2	2	2	1	4	2.125
670	0	1	1	2	1	1	2	1	1.125
680	2	0	3	5	1	2	7	4	3
690	0	0	0	2	0	1	0	0	0.375
700	1	0	0	1	1	1	0	2	0.75
710	4	1	2	1	1	0	6	0	1.875
720	0	1	1	3	3	1	0	2	1.375
730	0	0	0	5	0	0	4	2	1.375
Total	12	5	10	22	9	10	22	15	13.125

Table 25. Fatal and Injury Crash Frequencies for Study Area

Segment	2005	2006	2007	2008	2009	2010	2011	2012	Mean
650	1	2	2	1	0	0	1	0	0.875
660	1	0	0	2	0	1	0	0	0.5
670	0	0	1	2	0	1	1	1	0.75
680	1	0	1	2	0	1	2	4	1.375
690	0	0	0	1	0	0	0	0	0.125
700	1	0	0	0	0	0	0	0	0.125
710	1	0	2	0	0	0	0	0	0.375
720	0	0	1	2	1	1	0	0	0.625
730	0	0	0	3	0	0	1	1	0.625
Total	5	2	7	13	1	4	5	6	5.375

Assumptions

None

Results

Using the predictive method outlined below and applying the Empirical Bayes correction, the predicted frequency of total crashes for this roadway section is 13.1 crashes per year and the predicted frequency of fatal and injury crashes is 5.5 crashes per year.

Steps

Step 1 – Define the spatial limits of the study
The limit of this study is provided directly by the problem statement and includes only the section of SR 322 illustrated in Figure 1. This section contains roadway segments 650 through 730.

Step 2 – Define the period of interest
In this problem the analysis period of interest is 2013. However, as will be shown below, historical crash and traffic volume data will be required, and estimates of crash frequency estimated, for a period of several years before the analysis year to apply the Empirical Bayes adjustment. As shown in the Facts section, for this segment the data required for these estimations are available for the years 2005 to 2012.

Step 3 – Determine the availability of traffic volume and historical crash data
As per the Facts section, these information are available from the PennDOT RMS database.

Step 4 – Determine geometric design and other site characteristics
As per the Facts section, these information are available from the PennDOT RMS database and the supplemental data collected and provided by Penn State to PennDOT.

Step 5 – Divide the roadway network into individual segments

As per the Facts section, the PennDOT RMS database disaggregates individual roadways into multiple segments as a way to describe geometric and traffic data. Since the required information, such as access density and curve characteristics, has already been collected on the segment level, we will use these segments to perform the safety analysis.

Step 6 – Assign crashes to individual roadway segments

The PennDOT crash database provides the location of each crash in terms of the segment in which it occurred. This information has been provided in the Facts section.

Step 7 – Select an individual site in the study network

We select the first segment in the roadway section (segment 650) to illustrate the application of the safety performance functions (SPFs).

Step 8 – Select an individual analysis year in the period of interest

We select the year 2013 to illustrate the application of the safety performance functions (SPFs).

Step 9 – Determine and apply the appropriate SPF for the selected site

We apply the "short-form" version of the SPFs developed for two-lane rural roadway segments in Pennsylvania to be consistent with the Highway Safety Manual methodology. As described in Appendix C of this report, this short-form SPF assumes HSM base conditions for many of the geometric characteristics. For the total crash frequency, the short form SPF for total crash frequency on two-lane rural roadway segments in Pennsylvania is:

$$N_{cr,pr} = Length \times AADT^{0.754} \times e^{-5.894}$$

where:

$N_{cr,pr}$	= predicted total crash frequency on the segment (crashes/year);
Length	= length of segment (miles); and,
AADT	= annual average daily traffic on the segment (veh/day).

This equation can be evaluated by plugging the values provided for segment 650 in Table 23 into the equation, as follows:

$N_{cr,pr} = 0.4477 * (11171)^{0.754} * e^{-5.894} = 1.392$ crashes/year.

Therefore, the SPF predicts 1.392 total crashes to occur in 2013 based on the observed traffic volume and length of segment 650 under the "base" conditions.

For fatal and injury crash frequency, the short form SPF is:

$$N_{cr,pr} = Length * AADT^{0.735} * e^{-6.323}$$

where $N_{cr,pr,FI}$ is the predicted fatal and injury crash frequency on the segment (in terms of crashes/year) and the other variables have been previously defined. This equation can be evaluated by plugging the values provided for segment 650 in Table 22 and Table 23 into the equation, as follows:

$N_{cr,pr,FI} = 0.4477 * (11171)^{0.735} * e^{-6.323} = 0.759$ crashes/year.

Therefore, the SPF predicts 0.759 fatal and injury crashes to occur in 2013 based on the observed traffic volume and length of segment 650 under the "base" conditions.

Step 10 – Apply the appropriate CMFs for the segment

We must now adjust the crash frequency predictions to accommodate differences between the geometric characteristics of the segment of interest and the base conditions assumed. As discussed in Appendix C, the short-form version of the SPF for crash frequency on two-lane rural roadway segments assumes the following base conditions: a roadside hazard rating of 3 or less, no passing zones, no shoulder rumble strips, 5 access points per mile, and no horizontal curves. Since these attributes are included in the SPFs presented in Tables 2 and 3, we can use these model outputs to obtain Pennsylvania-specific CMFs for the following characteristics on two-lane rural roadway segments: roadside hazard rating, passing zones, shoulder rumble strips, access density, horizontal curve density and degree of curvature per mile. Differences from this particular set of base conditions can be incorporated using the CMFs based on the SPF models provided in Table 2. Differences in any other variables from the base conditions presented in the HSM (e.g., lane width or shoulder width) must be accommodated using the CMFs provided in the recently developed Pennsylvania CMF guide.

Segment 650 differs from the base conditions since it has a roadside hazard rating of 4, includes the presence of shoulder rumble strips, has access points along the roadway segment, and includes horizontal curves. The individual CMFs for total crash frequency are shown below (see Appendix C for their derivation):

$Combined\ CMF\ total\ crash\ frequency = e^{0.101RHR_{6,7}} * e^{0.091RHR_{4,5}} * e^{-0.239PZ} * e^{-0.188SRS} * e^{0.008(AD-5)} * e^{0.03HCD} * e^{0.002DCPM}$,

where:

- *RHR6,7* = roadside hazard rating on the segment of 6 or 7 (1 if RHR is 6 or 7; 0 otherwise);
- *RHR4,5* = roadside hazard rating on the segment of 4 or 5 (1 if RHR is 4 or 5; 0 otherwise);

PZ = presence of a passing zone in the segment (1 if present; 0 otherwise);
SRS = presence of shoulder rumble strips in the segment (1 If present; 0 otherwise);
AD = access density in the segment, total driveways and intersections per mile of segment length (Access Points/Mile);
HCD = horizontal curve density in the segment, number of curves in the segment per mile (Hor. Curves/Mile); and,
$DCPM$ = total degree of curvature per mile in the segment, the sum of degree of curvature for all curves in the segment divided by segment length in miles (Degrees/100 ft/Mile).

Applying the site-specific conditions for segment 650 provided in Table 22, we find that:

$Combined\ CMF\ total\ crash\ frequency = e^{0.101(0)} * e^{0.091(1)} * e^{-0.239(0)} * e^{-0.188(1)} * e^{0.008(8.934-5)} * e^{0.03(2.234)} * e^{0.002(7.817)} = 1.017.$

The predicted total crash frequency for segment 650 in 2013 is simply the product of the predicted value using the short-form SPF and the combined CMF that provides the adjustment from the base conditions: $1.392 * 1.017 = 1.416$ crashes/year.

Similarly, the CMFs for total and injury crash frequency are:

$Combined\ CMF\ fatal\ and\ injury\ crash\ frequency = e^{0.051RHR_{6,7}} * e^{0.055RHR_{4,5}} * e^{-0.232PZ} * e^{-0.184SRS} * e^{0.008(AD-5)} * e^{0.031HCD} * e^{0.002DCPM}.$

Applying the site-specific conditions for segment 650 provided in Table 22, we find that:

$Combined\ CMF\ fatal\ and\ injury\ crash\ frequency = e^{0.051(0)} * e^{0.055(1)} * e^{-0.232(0)} * e^{-0.184(1)} * e^{0.008(8.934-5)} * e^{0.031(2.234)} * e^{0.002(7.817)} = 0.987.$

The predicted fatal and injury crash frequency for segment 650 in 2013 is simply the product of the predicted value from the short-form SPF and the combined CMF that provides the adjustment from the base conditions: $0.759 * 0.987 = 0.749$ crashes/year.

Step 11 – Multiply the result by the appropriate calibration factor
Since we are applying SPFs created specifically for two-lane rural roads in Pennsylvania, which were developed using historical crash data from Pennsylvania, no calibration factor is required to modify the predictions of the SPFs.

Step 12 – Repeat Steps 8 to 11 for the remaining analysis years
Since crash frequency predictions are eventually needed for years 2005 to 2013, these steps were repeated for those analysis years. The results are summarized in Table 26 below.

Table 26. Crash Frequency Predictions for Segment 650 for All Analysis Years

Year	Predictions from SPFs for Segment 650	
	Total Crashes	Fatal and Injury Crashes
2005	1.450	0.767
2006	1.461	0.773
2007	1.452	0.768
2008	1.452	0.768
2009	1.452	0.768
2010	1.452	0.768
2011	1.452	0.768
2012	1.452	0.768
TOTAL	11.622	6.150

Step 13 – Apply the Empirical Bayes (EB) method to adjust results for observed crash frequency

For a more rigorous statistical prediction, an Empirical Bayes (EB) adjustment can be applied to the crash predictions. The EB method uses a weighted average between observed crash history for a site and the predicted frequency from the SPF to obtain a better estimate of predicted crash frequency, as described in the equation below:

$$N_{EB} = W * N_{pr} + (1 - W) * N_{obs}$$

where:

- N_{EB} – EB adjusted predicted crash frequency (crashes/year);
- W – weight for EB adjustment;
- N_{pr} – predicted crash frequency from the SPF (crashes/year); and,
- N_{ob} – observed mean crash frequency from crash history (crashes/year).

The weighting factor, W, is based on the crash frequency predicted by the SPF, number of years of historic crash data, and the overdispersion parameter obtained from the SPF model:

$$W = \frac{1}{1 + \frac{\sum N_{pr,ch}/L}{\varphi}}$$

where:

- W – weight for EB adjustment;
- $\sum N_{pr,ch}$ – sum of predicted crash frequency for each year of crash history;
- L – segment length (miles); and,
- φ - overdispersion parameter from the SPF model.

The overdispersion parameter for the total crash frequency SPF is 0.514. Using this information, the weighting factor for the estimate of total crash frequency is:

$$W = \frac{1}{1 + \frac{11.623/0.4477}{0.514}} = 0.019$$

The EB adjusted predicted crash frequency for Segment 650 in 2013 is then:

$$N_{EB} = 0.019 * 1.416 + (1 - 0.019) * 1.125 = 1.131 \; crashes/year$$

Because so little weight is given to the SPF prediction, the EB adjusted prediction is much closer to the crash history mean than the prediction. This occurs because there is a lot (eight years) of historical crash data available for the roadway segment. This process can be repeated for the Fatal and Injury crash prediction, for which the SPF has an overdispersion parameter of 0.624.

Step 14 – Apply the methodology to other sites or segments

The results of applying the SPFs and EB adjustment for total crashes on all segments as well as fatal and injury crashes on all segments are shown below in Table 27.

Table 27. Summary of Predict Crash Frequencies and Crash Frequencies Accounting for the EB Adjustment

Segment	Total Crashes				Fatal and Injury Crashes			
	Observed Mean	SPF, No EB	Weight	EB-Adjusted	Observed Mean	SPF, No EB	Weight	EB-Adjusted
650	1.125	1.416	0.019	1.131	0.875	0.749	0.043	0.870
660	2.125	1.697	0.017	2.118	0.500	0.900	0.038	0.515
670	1.125	1.589	0.017	1.133	0.750	0.842	0.037	0.753
680	3.000	1.910	0.017	2.981	1.375	1.013	0.038	1.361
690	0.375	1.282	0.019	0.393	0.125	0.679	0.044	0.149
700	0.750	1.468	0.018	0.763	0.125	0.779	0.041	0.152
710	1.875	1.566	0.019	1.869	0.375	0.829	0.042	0.394
720	1.375	1.579	0.020	1.379	0.625	0.834	0.044	0.634
730	1.375	1.688	0.019	1.381	0.625	0.894	0.043	0.637
Total	13.125	14.196		13.147	5.375	7.519		5.465

Step 15 – Apply the project-level EB adjustment

This step is not applicable for the segment level SPFs developed for the two-lane rural roads in Pennsylvania.

Step 16 – Sum crash frequencies across analysis years and locations

This sum is provided in Table 27 above.

Step 17 – Determine if there is an alternative design to be evaluated

No alternatives are proposed for this roadway section so this step is not needed.

Step 18 – Evaluate and compare results
Since multiple alternatives are not being compared, this step is not needed. The predicted total crash frequency for the roadway section is 13.1 crashes per year and for fatal and injury crash frequency is 5.5 crashes per year.

Case study 2 – Comparing Proposed Alternatives for an Existing Intersection

<u>The site/facility</u>

The intersection of SR 322 and SR 144. A satellite image of its current geometric configuration is provided in Figure 2.

Figure 2. Current Geometric Configuration for the Intersection of SR 322 and SR 144

<u>The question</u>

Geometric design changes are proposed for the intersection of SR 322 and SR 144. Engineers are planning to redesign the intersection from its current configuration (shown in Figure 2) to a simpler, more traditional, 3-leg configuration with stop-control on the minor approach. Four different configuration alternatives are being considered:

1. 3-leg configuration with no exclusive turn lanes.
2. 3-leg configuration with an exclusive left-turn lane on the major approach.
3. 3-leg configuration with an exclusive right-turn lane on the major approach.
4. 3-leg configuration with exclusive left- and right-turn lanes on the major approach.

The question then is which of the configurations will provide the best expected safety performance (i.e., lowest crash frequency) in a future year scenario 2015?

Facts

Traffic volumes (measured in AADT) for the future year scenario for which the project is expected to be completed are provided in Table 28. This information can usually be obtained from the relevant planning office or, as was done here, by extrapolating historical trends to the future year scenario.

Table 28. Future Traffic Volumes for Study Site

Intersecting Route	AADT in 2015 [veh/day]
Major approach (SR 322)	10981
Minor approach (SR 144)	4261

Assumptions

None

Results

Using the predictive method outlined below, the configuration alternative that provides the lowest crash frequency is alternative 2 (a 3-leg intersection with an exclusive left-turn lane only). The predicted frequency of total crashes for this proposed intersection configuration is 2.3 crashes per year and the predicted frequency of fatal and injury crashes is 1.3 crashes per year.

Steps

Step 1 – Define the spatial limits of the study

The limit of this study is the intersection of SR 322 and SR 144. In practice, the influence area of any intersection extends 250 feet upstream of each of the intersection approaches. Thus, the predictions performed here will account for crashes within this influence area.

Step 2 – Define the period of interest

In this problem, the analysis period of interest is the future year 2015.

Step 3 – Determine the availability of traffic volume and historical crash data

As per the Facts section, this information would be either available from the relevant planning authority or can be extrapolated from the current historical trends found in the current PennDOT RMS database.

Step 4 – Determine geometric design and other site characteristics

This information is usually available from the PennDOT RMS database and the supplemental data collected and provided by Penn State to PennDOT. For this problem, the geometric data is provided by the configuration alternatives being considered.

Step 5 – Divide the roadway network into individual sites

As given by the problem statement, only one site is being considered: the intersection of SR 322 and SR 144.

Step 6 – Assign crashes to individual sites

This step is not applicable since the analysis period represents a future year scenario for which historical crash data would not be available.

Step 7 – Select an individual site in the study network

Since only one site is being considered, this is the only site that will be selected.

Step 8 – Select an individual analysis year in the period of interest

Since the period of interest is just the future year 2015, this year is selected.

Step 9 – Determine and apply the appropriate SPF for the selected site

From Table 16, the short-form SPF for total crash frequency on 3-leg minor-stop control intersections of two-lane rural roads in Pennsylvania under the base conditions of no exclusive left-turn or right-turn lanes is:

$$N_{pr,3st} = AADT_{maj}^{0.479} * AADT_{min}^{0.362} * e^{-6.337}$$

where:

$N_{pr,3st}$ = predicted total crash frequency at the intersection (crashes/year);
$AADT_{maj}$ = annual average daily traffic on the major approach (veh/day); and,
$AADT_{min}$ = annual average daily traffic on the minor approach (veh/day).

This equation can be evaluated by plugging in the traffic volumes provided from the site data into the equation, as follows:

$N_{pr,3st} = (10981)^{0.479} * (4261)^{0.362} * e^{-6.337} = 3.142$ crashes/year

Therefore, based on the traffic characteristics of the intersection and proposed configuration, the SPF predicts 3.142 total crashes to occur in the future year scenario 2015 under base conditions.

Similarly, from Table 16, the short-form SPF for fatal and injury crash frequency on 3-leg minor-stop controlled intersections of two-lane rural roads in Pennsylvania under the base conditions of no exclusive left-turn or right-turn lanes is:

$$N_{pr,3st,FI} = AADT_{maj}^{0.439} * AADT_{min}^{0.343} * e^{-6.457}$$

where $N_{pr,3st,FI}$ is the predicted fatal and injury crash frequency at the 3-leg minor-stop controlled intersection (in terms of crashes/year) and the other variables have been previously defined. This equation can be evaluated by plugging in the values provided from the site data for the proposed configuration alternative 1 into the equation, as follows:

$$N_{pr,3st,FI} = (10981)^{0.439} * (4261)^{0.343} * e^{-6.457} = 1.639\ crashes/year$$

Therefore, based on the traffic characteristics of the intersection and proposed configuration, the SPF predicts 1.639 fatal and injury crashes in the future year scenario 2015 under base conditions.

Step 10 – Apply the appropriate CMFs for the segment
We must now adjust the crash frequency predictions to accommodate differences between the geometric characteristics of the segment of interest and the base conditions assumed. For the SPF developed for 3-leg minor-stop controlled intersections of two-lane rural roadways, the base conditions assume that no exclusive left-turn or right-turn lanes are provided. From the SPF output presented in Table 16, Pennsylvania-specific CMFs can be created for the presence of exclusive left-turn and right-turn lanes. Since the first alternative being considered includes no exclusive turn lanes, these CMFs do not apply and this step can be skipped for this specific alternative.

Step 11 – Multiply the result by the appropriate calibration factor
Since we are applying SPFs created specifically for intersections of two-lane rural roads in Pennsylvania, which were developed using historical crash data from Pennsylvania, no calibration factor is required to modify the predictions of the SPFs.

Step 12 – Repeat Steps 8 to 11 for the remaining analysis years
This step is not required since only a single analysis year is being considered.

Step 13 – Apply the Empirical Bayes (EB) method to adjust results for observed crash frequency
For simplicity, this step is skipped since the future year scenario is 2015 and historical crash data is not available for the preceding years.

Step 14 – Apply the methodology to other sites or segments
Since no other site is being considered, this step is not required.

Step 15 – Apply the project-level EB adjustment
This step is not applicable for the intersection level SPFs developed for the two-lane rural roads in Pennsylvania.

Step 16 – Sum crash frequencies across analysis years and locations
Since only one location and analysis year is being considered, this step is not required.

Step 17 – Determine if there is an alternative design to be evaluated
In this problem, four alternatives are being considered and only the first was analyzed. The SPF equations can be applied to the features of the other configuration alternatives

to assess their safety performance for the future year 2015. A summary of the results are provided in Table 29.

Table 29. Summary of Results of the Four Intersection Configuration Alternatives

Alternative Number	Total crashes	Fatal and injury crashes
1	3.142	1.639
2	2.259	1.255
3	5.217	2.869
4	3.751	2.197

Step 18 – Evaluate and compare results
We now compare the crash frequencies estimated for the various alternatives. As shown in Table 29, configuration alternative 2 has the lowest estimated crash frequencies for both total and fatal and injury crashes of the four possibilities. Thus, this configuration was selected as having the best safety performance in the future year 2015 scenario.

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APPENDIX A

VIDEO PHOTOLOG DATA COLLECTION INSTRUCTIONAL GUIDE

The Video Log system is used by PennDOT to describe the automated collection of panoramic roadway imagery. This online system is beneficial because data collectors can see visual images of roadway conditions without having to drive into the field. In this way, fewer man-hours are required to collect field data that can be obtained visually. In this project, the video log system is used to collect three pieces of information: 1) roadside hazard ratings (RHR) of roadway segments; 2) intersection lane configurations (e.g., presence of left- or right-turn lanes on intersection approaches) at intersections of state-owned two-lane rural roads; and, 3) verify the presence and type of traffic control that exists at these intersections (e.g., two-way vs. all-way vs. signal control).

This document will demonstrate how to collect the data needed for this project using State Route 3009 in Bedford County as an example. Prior to demonstrating the methods to collect the data of interest to the present study, the procedure necessary to access the PennDOT video log system is described.

Step 1: Access the PennDOT Online Video Log system at the following link:
http://www.dot7.state.pa.us/VideoLog/Open.aspx
Internet Explorer will likely display a "pop-up blocker" for state.pa.us – allow this to display.

Step 2. After gaining access to the Pennsylvania Video Log Application, click "I Accept" (Figure 3).

Figure 1. Screenshot of *"I Accept"* Icon

Step 3. In the "Select Area of Interest" box that is shown in Figure 4, select "route segment". Click "Generate Map" when finished.

Figure 4. Screenshot for Select Area of Interest

Step 4. In the "County" and "Select a State Route" boxes shown in Figure 5, select Bedford County and SR 3009 as shown in Figures 6 and 7, respectively. Be sure to choose "Entire Route" when selecting the State Route as this will begin the video log at the first segment within the county.

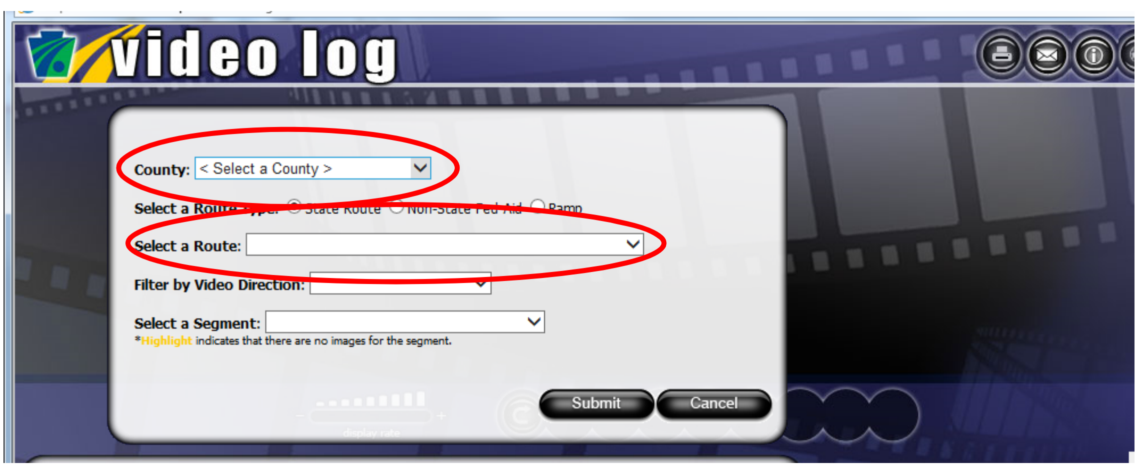

Figure 5. Select a County and Select a Route Screen Capture

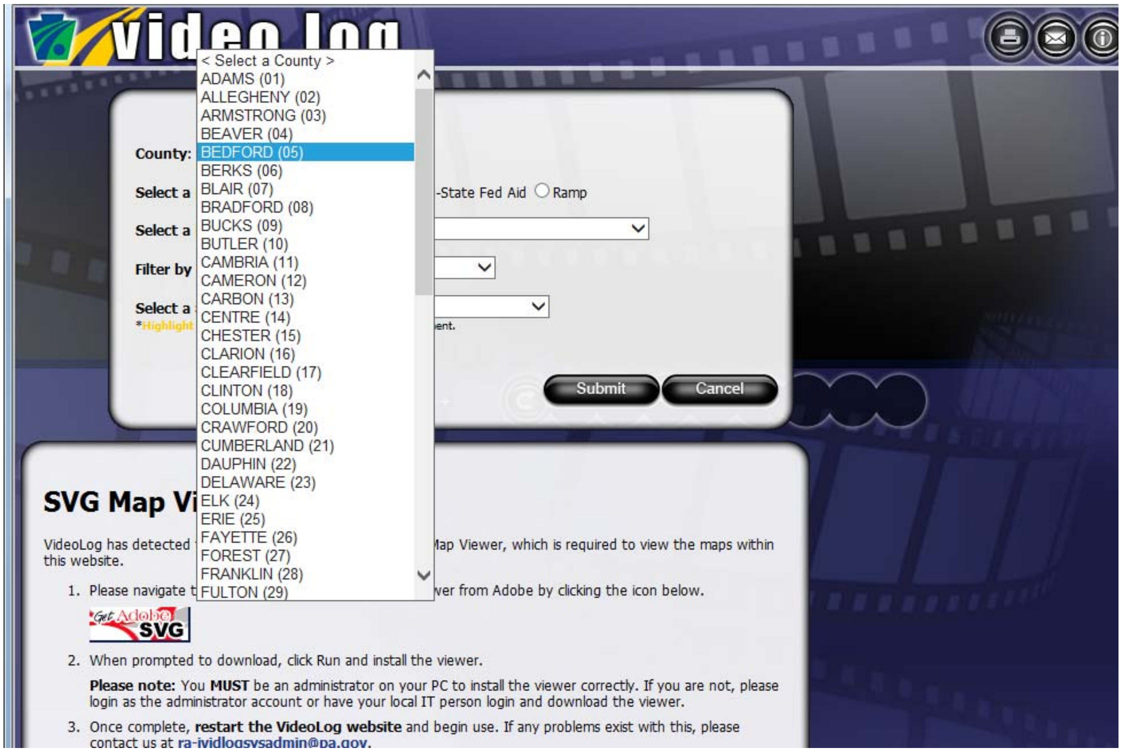

Figure 6. Selecting Bedford County

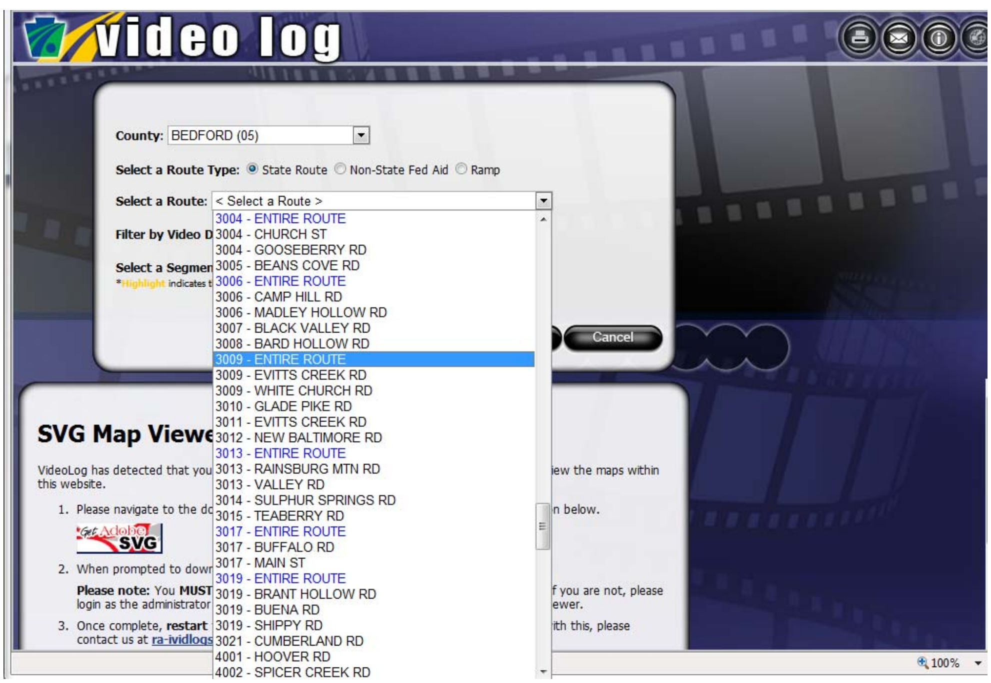

Figure 7. Selecting SR 3009

Step 5. When you gain access to the video log, click “***Activate Map***” (see Figure 8). A map will appear that provides a localized area map of the subject route, SR 3009 (see Figure 9). If you are using a computer that has not yet accessed the Pennsylvania Video Log application, you will need to install a map function Get Adobe SVG (see Figure 10), which has a link just below the video log picture.

Figure 8. The “*Activate Map*” Icon

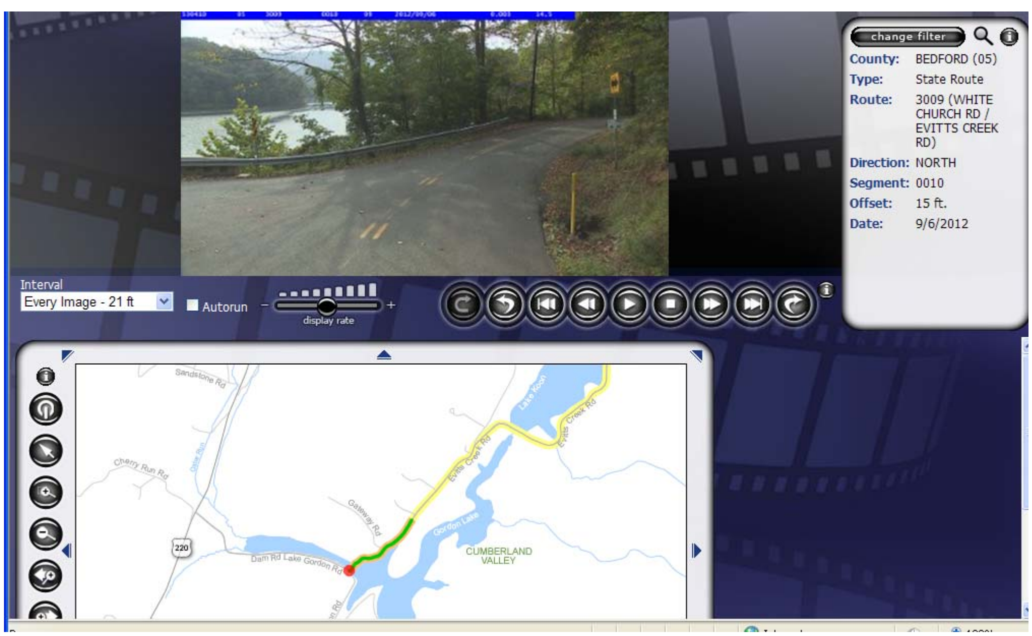

Figure 9. Screenshot for “*Show-up Map*” to locate beginning point for SR 3009

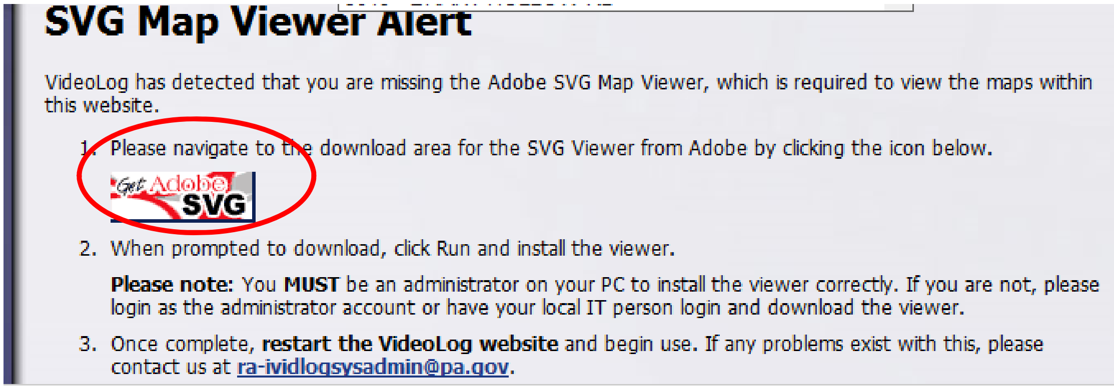

Figure 10. Screenshot for installing a map plug-in

The data that will be collected from the video log system are now described.

Roadside Hazard Rating (RHR)

The roadside hazard rating (RHR) is a qualitative characterization of the crash potential for roadside designs on two-lane highways. These estimates are made by visually inspecting a segment of roadway and assigning it a value based on the guidelines provided in Zegeer et al (1986). In this system, a seven-point categorical scale is used to describe the potential hazards, ranging from 1 (least hazardous) to 7 (more hazardous). For this project, we will utilize the PennDOT online video log system to estimate the RHR for all state-owned roadway segments on two-lane rural highways. A detailed description of roadside design features that "map" to each of the seven RHR categories are shown below, as are example graphics illustrating each rating category (Torbic et al, 2009):

Rating = 1

- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edge line.
- Side slope flatter than 1V:4H (Vertical:Horizontal).
- Recoverable (*meaning: the driver of a vehicle that departs the roadway section should be able to recover the vehicle and steer back onto the roadway*).

Figure 11. Typical Roadway with Roadside Hazard Rating Equal to 1.

Rating = 2

- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edge line.
- Side slope about 1V:4H.
- Recoverable.

Figure 12. Typical Roadway with Roadside Hazard Rating Equal to 2.

Rating = 3

- Clear zone about 3 m (10 ft) from the pavement edge line.
- Side slope about 1V:3H or 1V:4H.
- Rough roadside surface.
- Marginally recoverable.

Figure 13. Typical Roadway with Roadside Hazard Rating Equal to 3.

Rating = 4

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Side slope about 1V:3H or 1V:4H.
- May have guardrail 1.5 to 2 m [5 to 6.5 ft] from pavement edgeline.
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

Figure 14. Typical Roadway with Roadside Hazard Rating Equal to 4.

Rating = 5

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Side slope about 1V:3H.
- May have guardrail 0 to 1.5 m [0 to 5 ft] from pavement edgeline.
- May have rigid obstacles or embankment within 2 to 3 m (6.5 to 10 ft) of pavement edgeline.
- Virtually non-recoverable.

Figure 15. Typical Roadway with Roadside Hazard Rating Equal to 5.

Rating = 6

- Clear zone less than or equal to 1.5 m (5 ft).
- Side slope about 1V:2H.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Figure 16. Typical Roadway with Roadside Hazard Rating Equal to 6.

Rating = 7

- Clear zone less than or equal to 1.5 m (5 ft).
- Side slope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Non-recoverable with high likelihood of severe injuries from roadside collision.

Figure 17. Roadway with Roadside Hazard Rating Equal to 7.

Example

Again, consider State Route 3009 in Bedford County as an example. In this example, as in most segments, the roadside hazard rating (RHR) will be different for the two directions of travel within the segment limits. As such, data collectors should estimate the average of the RHR within the segment (i.e., produce only a single RHR measure per segment). Figures 11 through 17 were used to assign a RHR for each segment. Figures 18,19 and Table 29 show the process used to determine that SR 3009, Segment 0010 is category 6.

Figure 18. Video Log for SR 3009, Segment 0010.

Figure 19. Video Log for SR 3009 Segment 0010.

Table 29. The checklist of RHR for SR 3009 Segment 0010.

SR. 3009 seg. 0010 RHR						
	clear zone	side slope	Cliff or Vertical Rock	Guardrail	Rigid Obstacles	Recoverable
Rating 1	>=9 m(30 ft)	Flatter than 1:4	No	No	No	Yes
Rating 2	6-7.5 m(20-25 ft)	1:4			No	Yes
Rating 3	3 m(10 ft)	1:3 or 1:4			Rough roadside surface	Marginally
Rating 4	1.5-3 m(5-10 ft)			Allowable(1.5-2m[5-6.5ft])	About 3m(10ft)	Marginally forgiving
Rating 5		1:3		Allowable(0-1.5m[0-5ft])	2-3m(6.5-10ft)	Virtually non-recoverable
Rating 6	<=1.5 m(5 ft)	1:2		N/A	0-2m(0-6.5ft)	No
Rating 7		1:2 or steeper	Yes		N/A	No(high likelihood of injure)

SR 3009 segment 0010 is an example of a “severe” roadside. An example of a more forgiving roadside is shown in Figures 20 through 22, which is SR 3009, Segment 0090 in Bedford County. This example also illustrates how the RHR can change within the limits of a segment. Figure 20 shows how the RHR from both sides of the segment are averaged, while Figures 21 and 22 show how the RHR is averaged over the length of the segment. This process resulted in Segment 0090 being assigned a RHR of 3.

Figure 20. Video log for segment 0090 (1)

Figure 21. Video log for Segment 0090 (2)

Figure 22. Video log for Segment 0090 (3)

Intersection Lane Configurations and Verification of Traffic Control

The video log intersection data collection effort will be used to identify the presence of left or right-turn lanes on intersection approaches, and the type of traffic control present at intersections. For this project, we are only interested in the intersections of two state owned roads. Therefore, you should verify (using Google Maps or some other tool) that the intersection you observe in the video log is another state owned road.

The intersection control types considered in this research are: two-way stop control, all-way stop control, and signalized intersection control. Consider the intersection of SR 3009 with SR 3011 which is located within Segment 0150 in Bedford County. This is a two-way stop-controlled intersection that has no left turn lane or right turn lane.

Figure 23. Intersection Data Collection and Traffic Control

Other Segment-level Data

In the roadway segment data files, the following additional data will be collected and entered into the appropriate columns of the datafile:

- Presence of passing zones
- Presence of centerline or shoulder rumble strips
- Presence of horizontal curve warning pavement markings
- Presence of intersection warning pavement markings
- Presence of aggressive driving "dots"
- Number of driveways and intersections that are not considered the intersection of state-owned roadways.

An example of a passing zone on a two-lane highway is shown in Figure 24. Examples of shoulder (left panel) and centerline (left panel) rumble strips are shown in Figure 25. Figure 26 (left panel) shows an example of a horizontal curve warning pavement marking and the right panel of Figure 26 shows an example of intersection warning pavement markings. Aggressive driving "dots" are shown in Figure 27.

Figure 24. Example of passing zones.

Figure 25. Example of centerline rumble strips (left panel) and shoulder rumble strips (right panel).

Figure 26. Example of horizontal curve warning pavement marking (left panel) and intersection warning pavement marking (right panel).

Figure 27. Example of aggressive driving "dots" sign and pavement markings.

APPENDIX B

GOOGLE EARTH DATA COLLECTION INSTRUCTIONAL GUIDE

Google Earth is a virtual and geographic program where the 3D terrain and roadway features can be detected using detailed aerial maps. Specific tools within the Google Earth programs allow for a relatively precise way to measure linear distances and angles. For this project, Google Earth provides a useful and straightforward way to collect: 1) the geometric parameters describing horizontal curves; and, 2) the skew angle of intersections of two state owned roads.

The Google Earth tool is freely available online at: http://www.google.com/earth/index.html.

The low resolution of aerial imagery available for rural areas might result in variability in the definition of these horizontal curves among various data collectors. In an effort to alleviate this issue, we will also make use of PennDOT's video log system (available at: http://www.dot7.state.pa.us/VideoLog/Open.aspx) to help define the curve limits from a driver's perspective.

<u>Horizontal Curve Data Collection</u>

The geometric data that we are interested in for each horizontal curve includes: 1) the length of the curve (i.e., its arc length); and, 2) the radius of the curve. The following sections describe the specific processes used to collect this horizontal curve data.

Step 1: Drawing the route path in Google Earth

Since every state-owned rural two-lane route is coded in PennDOT's roadway files at the segment-level, horizontal curve data are defined within the segment boundaries. For each segment, we are interested in the number of horizontal curves that exist, and the radius and arc length of each. Before locating the starting and ending points for segments, we must first draw a path along a given route using Google Earth.

At the top of the order panel, click the "***Add Path***" icon (see Figure 28) . A window will appear to create a new path (see Figure 29). Give the path a name (e.g., SR 3009 in this example) and draw a path along the roadway of interest. This is done by clicking at points along the roadway to create nodes for the path. The nodes should be placed at fairly regular intervals (~500 ft) on straight sections, and should be placed much closer on horizontal curves to capture the curve geometry. After you have finished creating the path, click "***Ok***". **NOTE**: based on the way roadway segments are numbered in the PennDOT system, paths should be created from west to east and from south to north (i.e., direction of increasing segment).

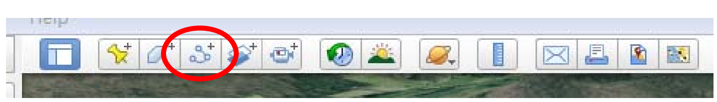

Figure 28. *"Add Path"* Icon

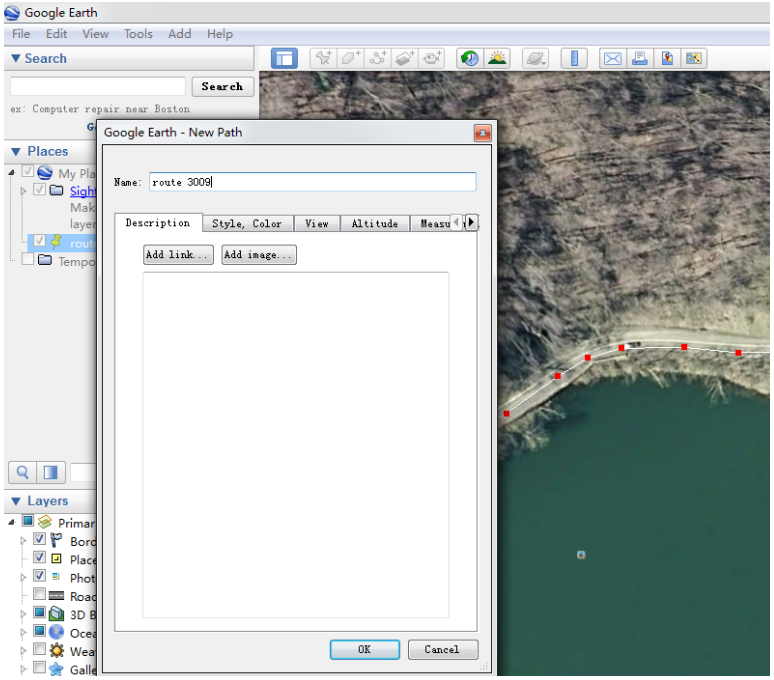

Figure 29. Screenshot for Adding Path

Step 2: Locating the starting and ending point for each segment

We must now determine the starting and ending point of each segment using the PennDOT roadway database. In Table 30, there are 18 contiguous segments on State Route (SR) 3009 in Bedford County. The first segment is 0010 while the last is 0180. The segment length in feet is provided in the fourth column, while a mileage-based segment length is shown in the fifth column. The cumulative length column is a measure of the roadway length within the county beginning at the western- or southern-most county boundary. Adjacent cumulative length values represent the beginning and ending mileposts for each segment along the route, which will be needed to use the Google Earth tool that is described in this document.

First and foremost, we need to find the beginning point for the entire route. Take segment 0010 in Bedford County as an example. When you gain access to the video log, which was illustrated in the video log sheet, a map will appear that provides a localized area map of the subject route, SR 3009 (see Figure 30). This will help you locate the starting point for the entire route. To find all the necessary locations on the Google Earth image, we will use the built-in ruler to add each segment length to the start point. Click ***"Show Ruler"*** (see Figure 31), and change the unit of length to "Feet", as shown in Figure 32.

Table 30. Length of Segments in PennDOT Profile

CNTY	SR	SEG	LENGTH(ft)	LENGTH(mi)	Begin Milepost	End Milepost	Cumulative length(mi)	SPEED	LANES	COUNTY
5	3009	10	2472	0.468182	0	0.468182	0.468182	55	2	BEDFORD
5	3009	20	2769	0.524432	0.468182	0.992614	0.992614	55	2	BEDFORD
5	3009	30	1271	0.240720	0.992614	1.233333	1.233333	55	2	BEDFORD
5	3009	40	3918	0.742045	1.233333	1.975379	1.975379	55	2	BEDFORD
5	3009	50	2929	0.554735	1.975379	2.530114	2.530114	55	2	BEDFORD
5	3009	60	1387	0.262689	2.530114	2.792803	2.792803	55	2	BEDFORD
5	3009	70	2577	0.488068	2.792803	3.280871	3.280871	55	2	BEDFORD
5	3009	80	2508	0.475000	3.280871	3.755871	3.755871	55	2	BEDFORD
5	3009	90	3015	0.571023	3.755871	4.326894	4.326894	55	2	BEDFORD
5	3009	100	2029	0.384280	4.326894	4.711174	4.711174	55	2	BEDFORD
5	3009	110	1963	0.371780	4.711174	5.082955	5.082955	55	2	BEDFORD
5	3009	120	2592	0.490909	5.082955	5.573864	5.573864	55	2	BEDFORD
5	3009	130	1937	0.366856	5.573864	5.940720	5.940720	55	2	BEDFORD
5	3009	140	1744	0.330303	5.940720	6.271023	6.271023	55	2	BEDFORD
5	3009	150	2312	0.437879	6.271023	6.708902	6.708902	55	2	BEDFORD
5	3009	160	1794	0.339773	6.708902	7.048674	7.048674	55	2	BEDFORD
5	3009	170	3978	0.753409	7.048674	7.802083	7.802083	55	2	BEDFORD
5	3009	180	2056	0.389394	7.802083	8.191477	8.191477	55	2	BEDFORD

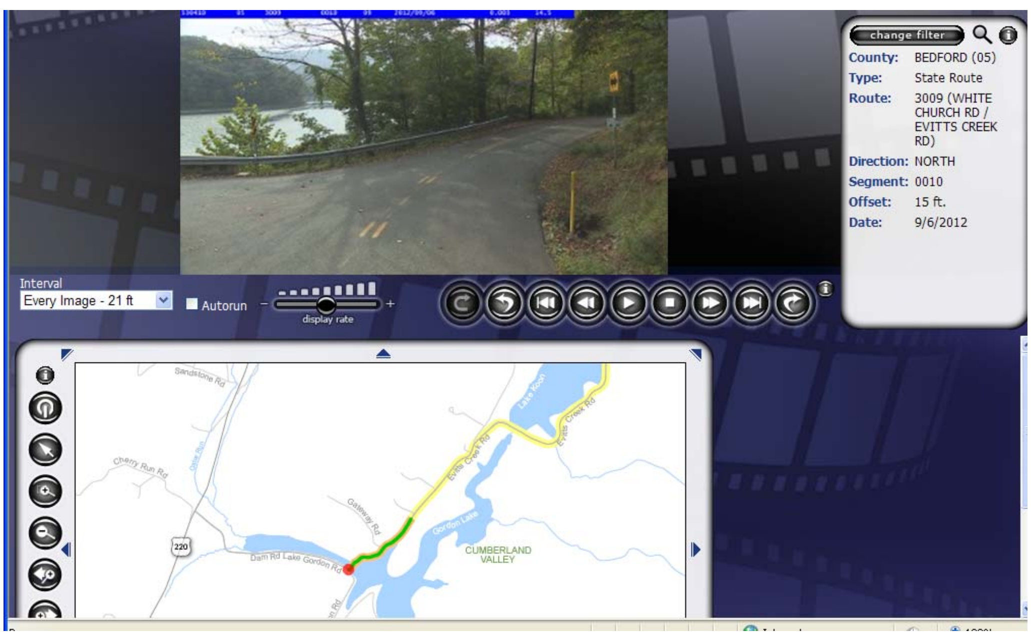

Figure 30. Screenshot for "*Show-up Map*" to locate beginning point for SR 3009

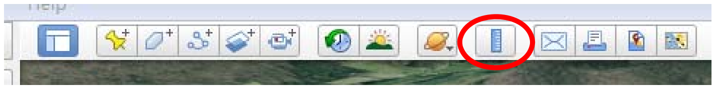

Figure 31. The "Show Ruler" Icon

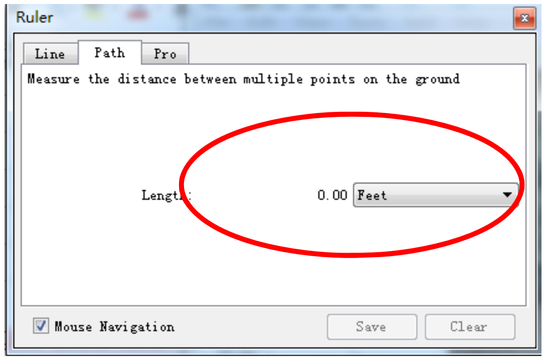

Figure 32. Screenshot for *"Show Ruler"* in The Starting Location

As shown in Table 30, the end of the first segment (0010) is 2472 ft from the start of the route in Bedford County. Using the ruler, measure a distance 2472 ft from the first point on the path. This location represents the end point of segment 0010 and the beginning point (offset 0000) of segment 0020. Save this location on the map. To do this, click ***"Save"*** and then click ***"Add Placemark"***  (see Figures 33 and 34). This will create a placemark that denotes the starting/ending point (see Figures 35 and 36).

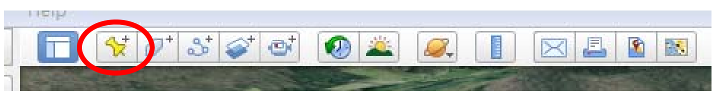

Figure 33. The *"Add Placemark"* Icon

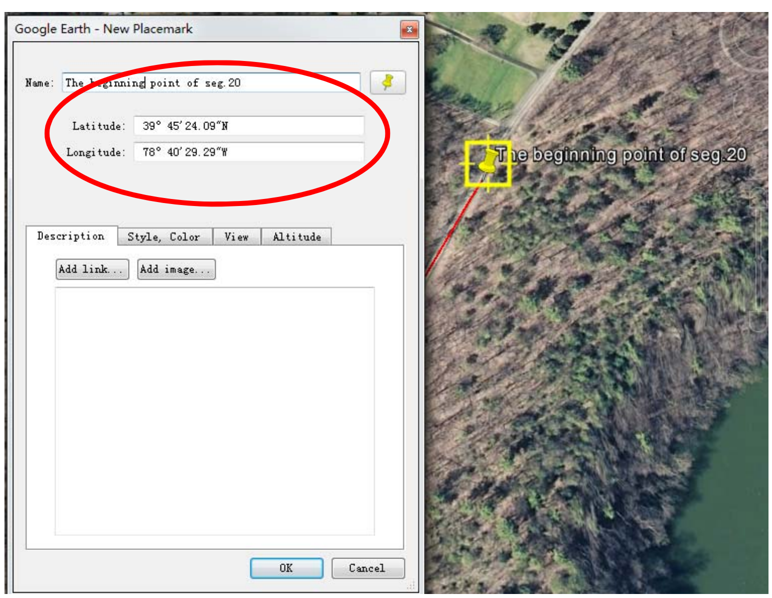

Figure 34. Screenshot for *"Add Placemark"*

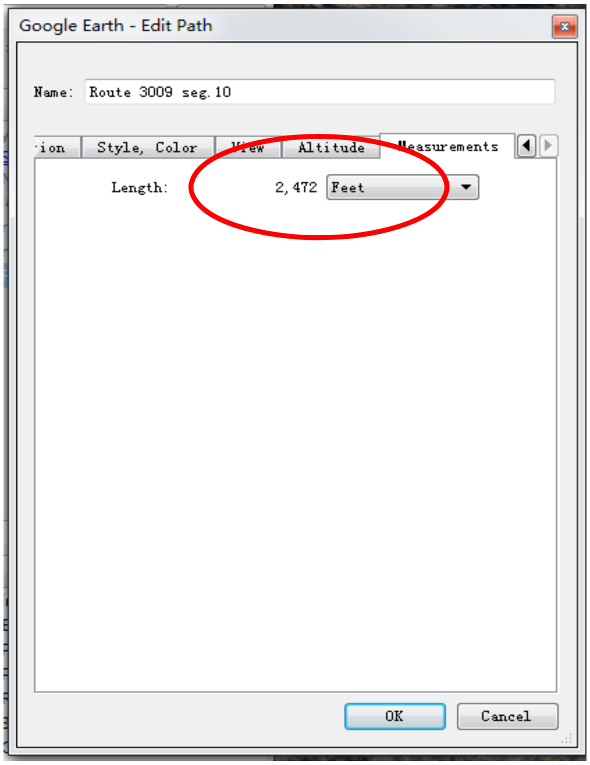

Figure 35. Locating the ending points of seg.10

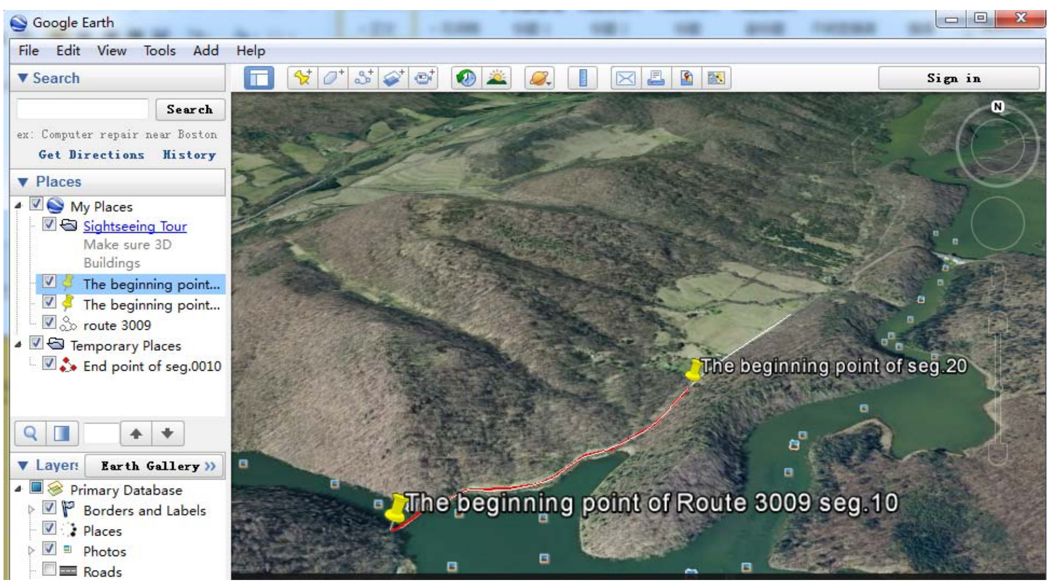

Figure 36. The Starting and Ending Points for Segments

Repeat this process for all segment starting/ending points along the route.

Step 3: Measuring Curves in Google Earth

Visually inspect each segment to identify any horizontal curves that exist based on your review of the video log. Once a curve has been identified from a driver's perspective, check the map below the video log to find the location and then go to Google Earth to confirm it. If this horizontal curve cannot be detected, scroll with the mouse to enlarge the picture. In order to keep consistently across individuals, we set up 1:1592.5cm (4cm: 209ft) as scale legend because the segment almost covers the whole screen in this zooming level (See Figure 37). This level helps when a big horizontal curve exists and stretches itself to another segment. Now, we will start to measure this curve's properties. Figure 38 shows the various components of a simple horizontal curve (AASHTO, 2011). Figure 39 shows how to apply each component on the Google Earth images. The radius of curve is "R" and the length of curve (arc) is denoted "L."

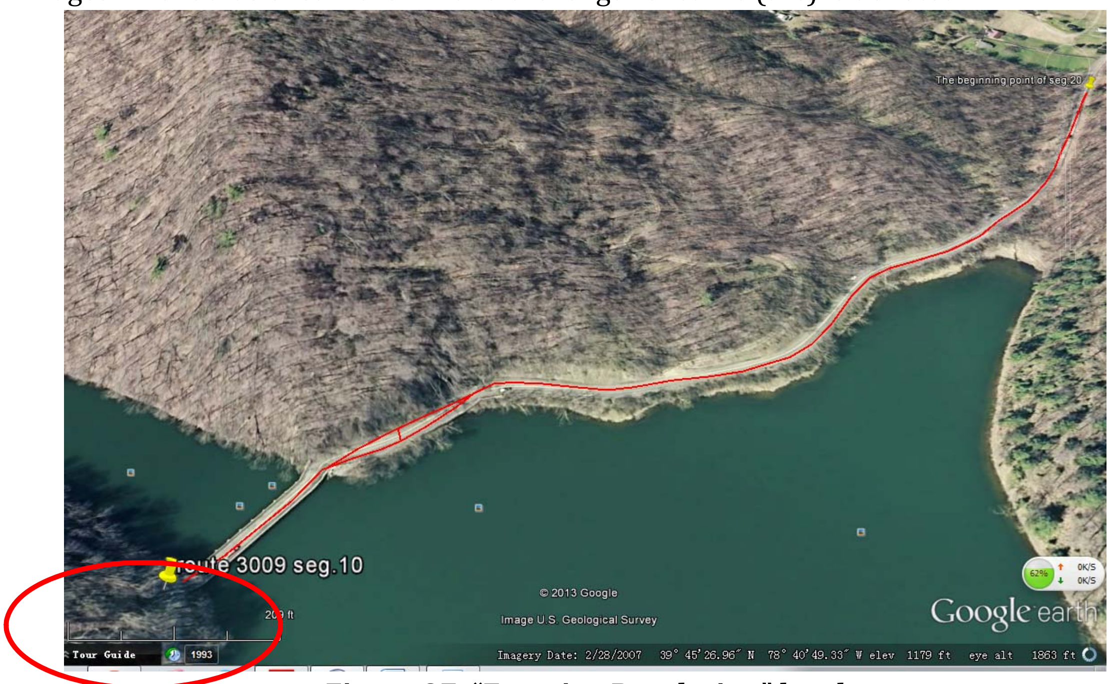

Figure 37. "Zooming Resolution" level

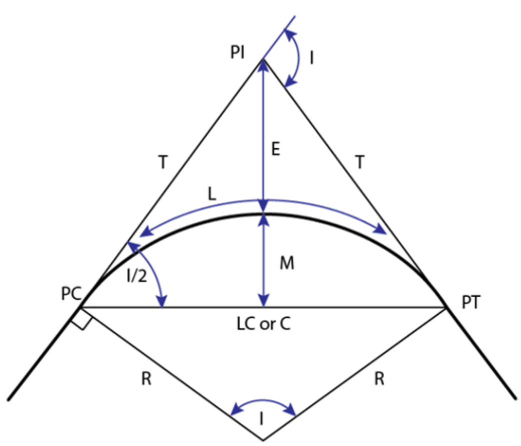

Figure 38. Measuring the length of arc and radius of the curve.

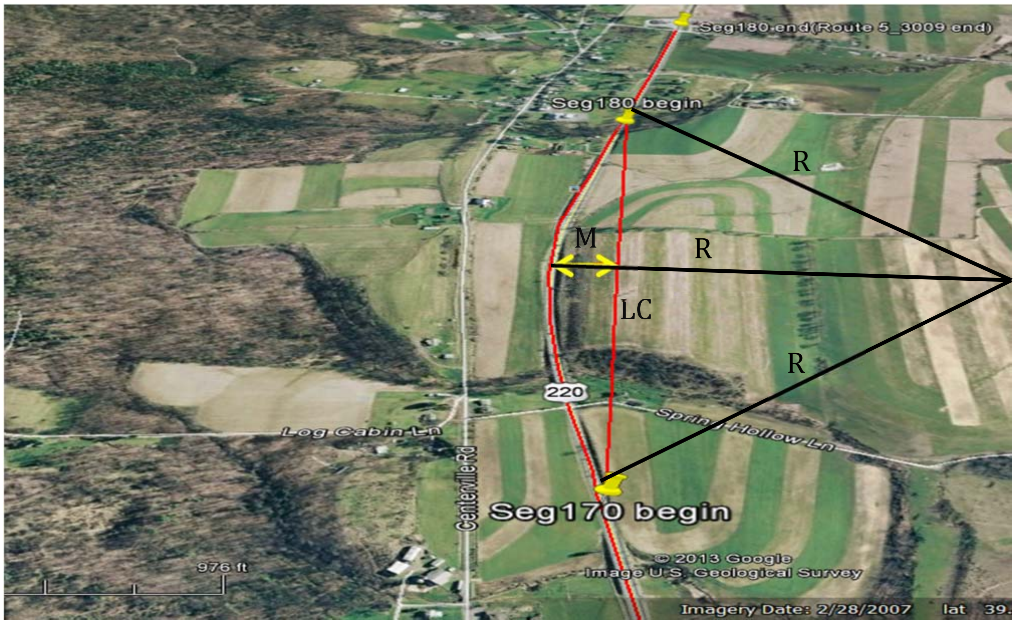

Figure 39. The Relationship between LC, M, and R

Based on the geometry of Figure 38 and Figure 39, the relationship between LC, M, and radius *R* is as follows:

$$(LC/2)^2 + (R-M)^2 = R^2 \qquad (10)$$
$$R = LC^2/8M + M/2 \qquad (11)$$

Consider a horizontal curve in segment 0010 of State Route 3009 in Bedford County, as an example. After identifying the curve using Google Earth, mark the two locations where the arc (length of curve) is adjacent to the intersecting tangents (labeled PC and PT in Figure 38), and record the coordinates of the PC (point of curve or beginning of curve in direction of increasing segment) and PT (point of tangent or end of curve in direction of increasing segment). This is done by clicking ***"Add Placemark"*** so you can move the yellow pin to gain the latitude and longitude information of the two points (an example is shown in Figure 40). Record the coordinates of these two points as shown in Table 31. The second procedure to measure the curve is to draw a chord (line LC or C in Figure 38) to connect the PC and PT. Then, draw a perpendicular line from the chord to the mid-point of the arc (line M in Figure 38), which is illustrated in Figures 41 and 42, respectively. Tables 32 and 33 illustrate how the data collector will populate the length of chord and mid-line length data into the respective cells.

Note that LC is the length of chord and M is the length of mid-point line, which can be calculated from the "***Show Ruler***" tool in Google Earth. The process used to access to the "***Show Ruler***" tool were noted above.

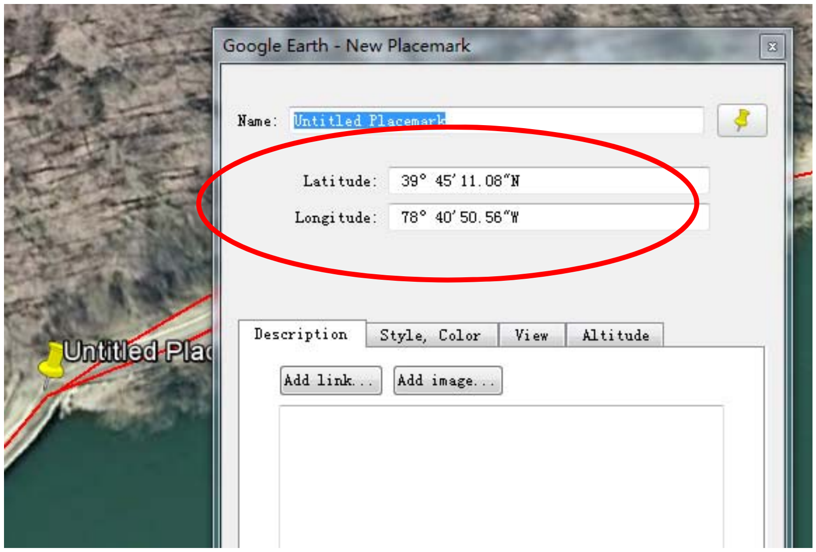

Figure 40. Example of Displaying Coordinates

Table 31. Filling in the Coordinates Data

CNTY	SR	SEG	LENGTH (ft)	Point of Tangents (PT) (1)	Length of chord(1) (LC,ft)	Mid-line length(1) (M,ft)	Radius in map(1) (ft)
5	3009	10	2472	(39°45'11.08"N, 78°40'50.56"W) (39°45'12.67"N, 78°40'47.93"W)	266.10	27.09	340.28

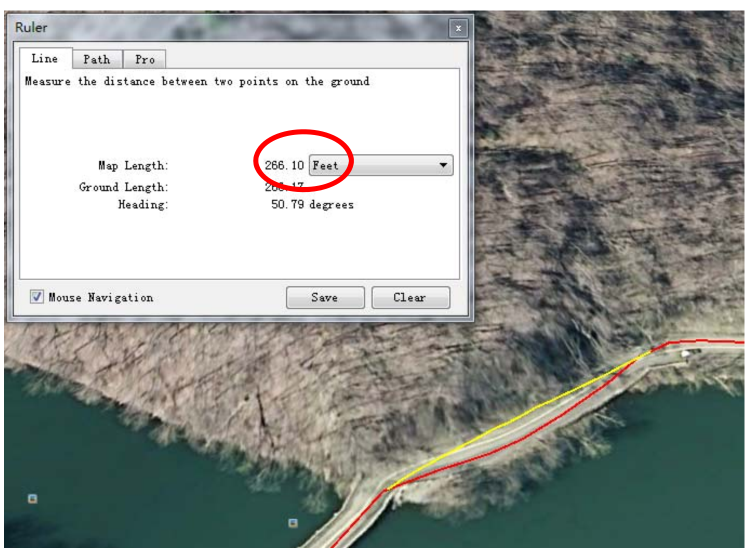

Figure 41. Example of Drawing the Chord

Table 32. Filling in Length of Chord Data

CNTY	SR	SEG	LENGTH (ft)	Point of Tangents (PT) (1)	Length of chord(1) (LC,ft)	Mid-line length(1) (M,ft)	Radius in map(1) (ft)
5	3009	10	2472	(39°45'11.08"N, 78°40'50.56"W) (39°45'12.67"N, 78°40'47.93"W)	266.10	27.09	340.28

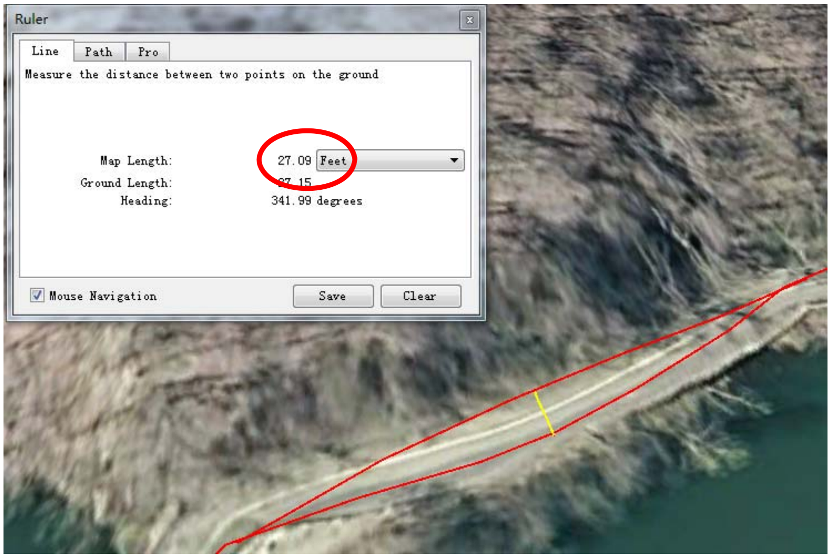

Figure 42. Example of Drawing the Mid-line

Table 33. Filling in Mid-line Data

CNTY	SR	SEG	LENGTH (ft)	Point of Tangents (PT) (1)	Length of chord(1) (LC,ft)	Mid-line length(1) (M,ft)	Radius in map(1) (ft)
5	3009	10	2472	(39°45'11.08"N, 78°40'50.56"W) (39°45'12.67"N, 78°40'47.93"W)	266.10	27.09	340.28

From equation (11), the radius (R) is derived from the LC and M terms. The results are displayed in Table 34. When a segment does not have any curves, put an **"X"** in the curve cells for that particular segment to designate that you have checked the segment and no curves exist. Similarly, if there are more than three curves in a current segment, insert more curve columns to the database, to the right of the existing curve data columns. Note that if a single horizontal curve crosses two adjacent segments, this curve should be "split" into two parts and recorded in the corresponding segment data cells. For example, if a horizontal curve begins in segment 0040 and continues into segment 0050, the horizontal curve component that exists in segment 0040 will be recorded in segment 0040, and the other component of the curve that exists in segment 0050 will be identified as another horizontal curve in segment 0050. The end point of the curve (PT) in segment 0040 should be equal to the beginning point of the curve (PC) in segment 0050.

Table 34. PT Coordinates, Length of chord, Mid-line Length and Radius of Curve

CNTY	SR	SEG	LENGTH (ft)	Point of Tangents (1) (PT)	Length of chord (1) (LC,ft)	Middle line length (1) (M,ft)	Radius on map (1) (ft)	Point of Tangents (2) (PT)	Length of chord (2) (LC,ft)	Middle line length (2) (M,ft)	Radius in map (2) (ft)	Point of Tangents (3) (PT)	Length of chord (3) (LC,ft)	Middle line length (3) (M,ft)	Radius io map (3) (ft)
5	3009	10	2472	(39°45'11.08"N, 78°40'50.56"W) (39°45'12.67"N, 78°40'47.93"W)	266.1	27.09	340.28	(39°45'12.61"N, 78°40'47.99"W) (39°45'16.01"N, 78°40'38.94"W)	780.00	138.74	617.52	(39°45'16.01"N, 78°40'38.94"W) (39°45'19.69"N, 78°40'32.92"W)	1119.32	113.50	1436.57
5	3009	20	2769	(39°45'40.62"N, 78°40'12.15"W) (39°45'45.77"N, 78°40'6.14"W)	705.97	144.85	502.52	X	X	X	X	X	X	X	X
5	3009	40	3918	(39°46'1.78"N, 78°39'19.77"W) (39°46'3.60"N, 78°39'18.04"W)	222.88	13.06	481.98	X	X	X	X	X	X	X	X
5	3009	50	2929	(39°46'3.60"N, 78°39'18.04"W) (39°46'5.27"N, 78°39'17.78"W)	172.65	8.62	436.56	X	X	X	X	X	X	X	X

Intersection Data Collection

When it comes to the intersection skew angle data collection, we can zoom in the Google Map to enlarge the intersection, and place the protractor on the computer screen to measure the skew angle of the intersection. The skew angle is the smallest angle between the two intersection roads, and should also be less than or equal to 90 degrees.

Figure 43. Intersection skew angle of SR 3009 and SR3012

APPENDIX C

Integrating the Pennsylvania Safety Performance Functions into the Highway Safety Manual Framework

This Appendix describes a process to integrate the safety performance functions (SPFs) developed for two-lane rural roadways in Pennsylvania directly into the Highway Safety Manual (HSM) framework. This is done by considering the roadway segment SPF. It is recommended that the integration of the intersection SPFs be completed in a similar manner. This Appendix includes the HSM framework (left column) and describes (in the right column) the locations where Pennsylvania-specific information can be substituted into the framework, including the SPFs, base conditions, and application of crash modification factors (CMFs).

Highway Safety Manual Framework

The HSM crash prediction algorithm for two-lane rural highways is as follows:

$$N_{predicted} = N_{spf\ x} \times \left(CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}\right) \times C_x$$

where: $N_{predicted}$ = predicted average crash frequency for a specific year for site type *x*;
$N_{spf\,x}$ = predicted average crash frequency determined for base conditions of the SPF developed for site type *x*;
CMF_{1x} = crash modification factors specific to site type *x* and specific geometric design and traffic control features *y*; and
C_x = calibration factor to adjust SPF for local conditions for site type *x*.

In the case of the predictive model shown above, site type *x* refers to a roadway segment or an intersection. For two-lane rural highway roadway segments, $N_{spf\,x}$ is computed as follows:

$$N_{spf\ x} = AADT \times L \times 365 \times 10^{-6} \times e^{(-0.312)}$$

The base conditions that are associated with $N_{spf\,x}$ are as follows:

- Lane width = 12 feet

Pennsylvania Framework

To integrate the Pennsylvania roadway segment SPF into the HSM framework, consider the general functional form of the SPF as shown below (see equation 7 in report):

$$\lambda_i = e^{\beta_0} \times L \times AADT^{\beta_1} \times e^{(\beta_2 X_2 + \ldots + \beta_n X_n)}$$

In this equation, substitute N_{spf} in place of λ_i for a parallel construct to the HSM framework. The remaining variables are defined as follows:

e = exponential function;
β_0 = regression coefficient for constant;
L = roadway segment length (miles);
$AADT$ = average annual daily traffic (veh/day);
β_1 = regression coefficient for average annual daily traffic on roadway segment;
$\beta_2, \ldots, \beta_n$ = regression coefficients for geometric design and other site-specific explanatory variables, $i = 2, \ldots, n$
$X_{2,} \ldots, X_n$ = vector of geometric design and other site-specific data;

Use the negative binomial regression coefficients in Table 2 of this report and substitute the values into the regression coefficients (b) to create the roadway segment SPF. The "full" SPF is as follows:

- Shoulder width = 6 feet
- Shoulder type = Paved
- Roadside hazard rating = 3
- Driveway density = 5 driveways per mile
- Horizontal curvature = None
- Vertical curvature = None
- Centerline rumble strips = None
- Passing lanes = None
- Two-way left-turn lanes = None
- Lighting = None
- Automated speed enforcement = None
- Vertical grade = Level (0%)

Note that similar base conditions exist in the HSM for the intersection SPFs for two-lane rural roads.

In Chapter 10 of the HSM, a series of CMFs may be applied to the crash prediction algorithm to adjust for site-specific conditions are not the same as the base conditions.

The HSM calibration procedure may be used to develop a numerical value for C_x in the crash prediction algorithm for jurisdictions whose data were not used to develop the HSM crash prediction algorithm. Because Pennsylvania data were not use to develop the HSM crash prediction algorithm, a C_x value derived from Pennsylvania is needed, or Pennsylvania-specific SPFs and CMFs can be developed. The purpose of the present study was to develop Pennsylvania-specific SPFs, so the HSM calibration factor (C_x) should be set equal to 1.0 for rural two-lane highway segments and intersections.

$$N_{spf} = e^{-5.934} \times L \times AADT^{0.754} \times e^{(0.101 \times RHR67 + 0.091 \times RHR45 - 0.239 \times PZ - 0.188 \times SRS + 0.008 \times AD + 0.030 \times HCD + 0.002 \times DCM)}.$$

where: N_{spf} = predicted average crash frequency for a specific year for a road segment (crashes per mile per year);
L = segment length (miles);
$AADT$= average annual daily traffic (vehicles per day);
$RHR67$ = 1 if roadside hazard rating is 6 or 7, 0 otherwise;
$RHR45$ = 1 if roadside hazard rating is 4 or 5, 0 otherwise;
PZ = 1 if passing zone is present, 0 otherwise;
SRS = 1 if shoulder rumble strips are present, 0 otherwise;
AD = number of intersections and driveways per mile;
HCD = number of horizontal curves per mile;
DCM = degree of curve per mile.

The base conditions assumed for the HSM can also be assumed for Pennsylvania. This includes a roadside hazard rating of 3, an access density of 5 per mile, no passing zones, no shoulder rumble strips, and no horizontal alignment. Applying these base conditions into the Pennsylvania-specific SPF above reduces the equation to the following:

$$N_{spf} = e^{-5.894} \times L \times AADT^{0.754}.$$

This is the “short-form” version of the SPF that is consistent with the HSM analysis framework.

CMFs for lane width, shoulder width, shoulder type, vertical curvature, presence of centerline rumble strips, presence of two-way left-turn lanes, presence of roadway lighting, presence of automated enforcement, and vertical grade cannot be developed directly from the long-form Pennsylvania-specific SPF above, so the HSM CMFs for these geometric and other site-specific features should be used in Pennsylvania. For the roadside hazard rating, presence of passing zones, access density, presence of shoulder rumble strips, and horizontal alignment, CMFs for Pennsylvania may be derived from the long-form SPF above. These CMFs are as follows:

$$CMF_{RHR} = e^{\left(0.101 \times RHR67 + 0.091 \times RHR45\right)}$$

CMF_{RHR} = CMF for roadside hazard rating
RHR67 = 1 if roadside hazard rating is 6 or 7, 0 otherwise;
RHR45 = 1 if roadside hazard rating is 4 or 5, 0 otherwise.

$$CMF_{PZ} = e^{(-0.239 \times PZ)}$$

CMF_{PZ} = CMF for presence of passing zone
PZ = 1 if passing zone is present, 0 otherwise.

$$CMF_{SRS} = e^{(-0.188 \times SRS)}$$

CMF_{SRS} = CMF for presence of shoulder rumble strips;
SRS = 1 if shoulder rumble strips are present, 0 otherwise.

$$CMF_{AD} = e^{0.008 \times (AD - 5)}$$

CMF_{AD} = CMF for access density;
AD = number of intersection and driveways per mile.

$$CMF_{HC} = e^{(0.030 \times HCD + 0.002 \times DCM).}$$

CMF_{HC} = CMF for horizontal curvature;
HCD = number of horizontal curves per mile;
DCM = degree of curvature per mile.