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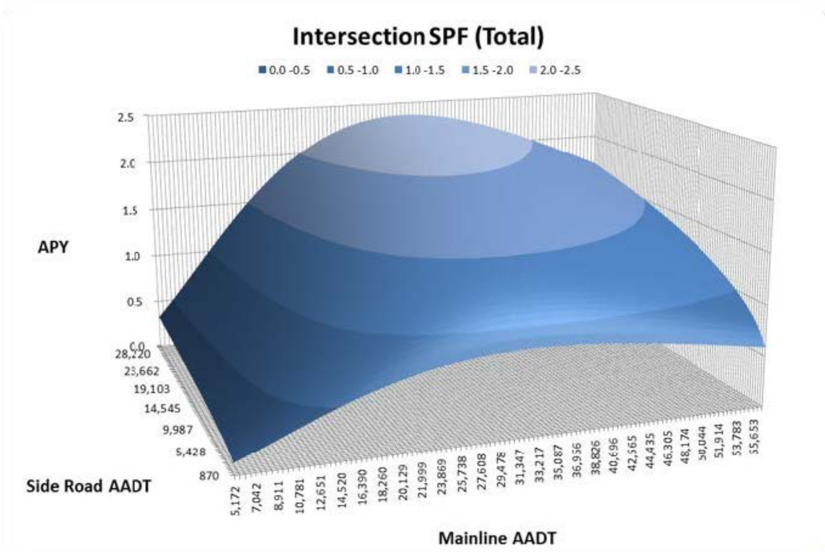
EVALUATING EFFECTIVENESS OF CRASH TYPE SPFs IN SAFETY MANAGEMENT

Comparing the Effectiveness of Network Screening and Diagnostic Methods Using Aggregate SPFs and Test of Proportion with Crash Type SPFs



Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Total Model

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16. Abstract
The intent of this project is to compare the effectiveness of network screening and diagnostic methods using aggregate SPFs and Test of Proportions with crash type SPFs. Both methods were applied to the same datasets containing crash history and exposure data. Sixteen (16) frequency and severity Colorado-specific crash type SPFs were developed for the following facilities: Rural 2 lane highways, Urban 4-Lane Divided Freeways, Urban 4-Lane, Urban 3-Leg, Divided, Unsignalized Intersections and Urban 4-Lane, 4-Leg, Divided, Signalized Intersections. These new models were used to evaluate and compare the effectiveness of both methods for diagnostics and network screening.

Implementation:
CDOT will consider incorporating the following findings in its safety management practices: 1) In some cases when two or more major crash types are concurrently elevated the overall number of crashes may be elevated without upsetting the balance of proportions among crash types. Such events happen infrequently but can't be detected by a test of proportions. 2)Test of proportion presently does not have a capability to detect elevated crash severity of a specific crash type. An effective strategy to remedy the situation is to develop stratified diagnostic norms for injury and fatal crashes only and to introduce injury focused level of diagnostic tests in addition to presently used tests for crashes of all severity.

17. Keywords
Predictive Modeling, Pattern Recognition, Empirical Bayes Method.

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EXECUTIVE SUMMARY

Since 2000 CDOT has made effective use of Safety Performance Functions (SPF), Level of Service of Safety (LOSS) concept and diagnostic norms to prioritize, plan and scope safety improvements on all projects. A recent trend in road safety research, however, is to develop SPFs for each crash type. This approach is significantly more costly and labor intensive than the one used by CDOT, the benefits of this approach, however, were not well understood. It was not known if having crash type-specific SPFs will improve effectiveness of safety management, or if it will simply make the process more labor-intensive and less accessible to practicing engineers and planners. The intent of this project is to compare the effectiveness of network screening and diagnostic methods using aggregate SPFs and Test of Proportions with crash type SPFs. Both methods were applied to the same datasets containing crash history and exposure data. Sixteen (16) frequency and severity Colorado-specific crash type SPFs were developed for the following facilities: Rural 2 lane highways, Urban 4-Lane Divided Freeways, Urban 4-Lane, Urban 3-Leg, Divided, Unsignalized Intersections and Urban 4-Lane, 4-Leg, Divided, Signalized Intersections. These new models were used to evaluate and compare the effectiveness of both methods for diagnostics and network screening.

The comparative analysis of network and diagnostic screenings using combined test of proportions based on stratified diagnostic norms in concert with aggregate SPF/LOSS analysis and using crash type-specific SPFs shows that present CDOT methodology is highly effective. Both methods, however, have some vulnerabilities that need to be addressed.

During diagnostic screening we observed that in some rare cases when two or more major crash types are concurrently elevated the overall number of crashes may be elevated *without upsetting the balance of proportions among crash types.* Such events happen infrequently but can't be detected by a test of proportions. For this reason, the diagnostic Test of Proportions should be supplemented with assessment of the magnitude of the safety problem using assessment of the aggregate LOSS levels. In addition to providing an important context for the diagnostic examination, doing so effectively guards against failing to identify locations having multiple crash types with elevated frequencies. In this study all locations identified by the Crash Type-

specific SPF at 95th percentile threshold but not diagnostic Test of Proportions performed at LOSS-IV reflecting high potential for crash reduction from the overall frequency or severity standpoints.

In the course of network screening we observed that test of proportion presently does not have a capability to detect elevated crash severity of a specific crash type. It only tests for elevated aggregate severity and overrepresentation in frequency of a specific crash type or attribute. It is possible that in some rare cases specific crash type at a location exhibits average frequency, but elevated severity. These circumstances may be missed by test of proportion and are not always reflected by the aggregate SPFs. An effective strategy to remedy the situation is to develop stratified diagnostic norms for injury and fatal crashes only and to introduce injury focused level of diagnostic tests in addition to presently used tests for crashes of all severity.

CDOT presently uses 13 segment and 25 intersection SPFs (frequency and severity models were developed for each facility type). If development of crash type-specific SPFs is contemplated it would require development of additional 152 frequency and severity models (assuming 4 major crash types per facility) which would need to be re-estimated every five years or so to reflect changes in safety performance. Considering that CDOT's present methodology is highly effective and institutionalized the additional effort of developing 152 new predictive models and maintaining them is not justified.

Implementation Strategy

CDOT will consider incorporating the following findings in its safety management practices:

1) In some cases when two or more major crash types are concurrently elevated the overall number of crashes may be elevated without upsetting the balance of proportions among crash types. Such events happen infrequently but can't be detected by a test of proportions. When elevated crash frequency or severity can't be readily explained by the presence of crash patterns the opportunities to reduce specific crash types should be evaluated in the site-specific context.

2)Test of proportion presently does not have a capability to detect elevated crash severity of a specific crash type. An effective strategy to remedy the situation is to develop stratified diagnostic norms for injury and fatal crashes only and to introduce injury focused level of diagnostic tests in addition to presently used tests for crashes of all severity. The findings in this report are expected to benefit CDOT's traffic and safety engineers in headquarters as well as in the regions.

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INTRODUCTION AND LITERATURE REVIEW

The concept of the Level of Service of Safety (LOSS) in the framework of Safety Performance Function (SPF) was developed at the Colorado Department of Transportation (CDOT) in 2000. LOSS reflects how a roadway segment, or an intersection is performing in reference to the expected frequency and severity of crashes predicted by its Safety Performance Function (SPF). It is extensively used for network screening and to provide quantitative assessment and qualitative description of the degree of safety of a segment or of an intersection. Additionally, it facilitates effective communication about safety problems to other professionals, the traveling public, and elected officials. The LOSS concept was first introduced in the 2003 TRB 1paper entitled Level of Service of Safety-Conceptual Blueprint and Analytical Framework. LOSS was incorporated into the first edition of the AASHTO Highway Safety Manual (HSM)2 and is presently used by the Colorado DOT, Wyoming DOT, Montana DOT, Louisiana DOT, Oklahoma DOT, Alabama DOT, Wyoming DOT and the Ontario Ministry of Transport. LOSS lends itself well to the safety decision making process in the DOT environment. However, it did not initially address correction for the Regression to the Mean (RTM) Bias. 2015 TRB paper entitled Level of Service of Safety Revisited introduces a new method for using LOSS in concert with correction for RTM bias using an Empirical Bayes (EB) procedure presently used by CDOT for network screening3.

The diagnostic method using binomial probability to conduct Tests of Proportions was initially introduced in the TRB Papers by Kononov[4] in 2002. This method was incorporated into Part B of the first Edition of the Highway Safety Manual (HSM) in 2010 (3). In this method, accident occurrence as a process is thought of as a sequence of Bernoulli trials. A framework of 84

[1] Kononov, J., and Allery, B. Level of Service of Safety-A Conceptual Blueprint and the Analytical Framework. *In Transportation Research Record 1840*, TRB, National Research Council, Washington, D.C., 2003, pp. 57-66

[2]Highway Safety Manual (HSM)1st Edition. American Association of State Highway and Transportation Officials. (AASHTO). Washington DC, 2010

[3] Kononov, J., K. Durso, C. Lyons, and B. Allery. Level of Service of Safety Revisited. Transportation Research Record: Journal of the Transportation Research Board, 2015. 2514: 10–20.

[4] Kononov, J., Identifying Locations with Potential for Accident Reduction-Use of Direct Diagnostics and Pattern Recognition Methodologies *In Transportation Research Record 1784*, TRB, National Research Council, Washington, D.C., 2002, pp. 153-158.

normative parameters was developed to provide a knowledge base for diagnostic analysis of different classes of highways and intersections in rural and urban environments. Using binomial probability, it is possible to detect deviation from the random statistical process by computing the observed cumulative probability for each of the 84 normative parameters. For example, it has been computed that at Colorado urban 6 lane, 4-leg, divided, signalized intersections, the average proportion (a diagnostic norm) of the left turn opposite crashes (referred to as approach turn by crash coders in Colorado) is 20.1%. If 55 approach turn crashes are observed out 159 crashes (159 Bernoulli trials) we can compute the cumulative probability of observing 55 of fewer approach turns as follows:

$$P(X \leq x) = B(x, n, p) = \sum_{i=0}^{x} \frac{n!}{(n-i)!i!} p^i (1-p)^{n-i}$$

$$P(X \leq 55, n = 159, p = 20.1\%) \approx 100\%$$

Where:

n – Total number of crashes (159)

x – Number of observed approach turn crashes (55)

p – Expected % approach turn crashes based on statewide statistics (20.1%)

P – Cumulative probability of observing x, here 55, approach turn crashes or fewer

Such a high cumulative probability strongly indicates that a location with 55 approach turn crashes out of 159 total crashes has a left turn problem that should be examined further and possibly addressed by introducing left turn protected-only phasing.

After applying this method in the 2002-2003 timeframe to diagnostics of safety problems of various highway design projects in Colorado, the authors observed that many, although not all, diagnostic norms change with congestion. Based on this experience, Kononov and Allery[1], in their 2003 TRB Paper, reported a problem with assumption of homogeneity in proportion of crash types and suggested a work around by stratifying facility-specific diagnostic norms by the degree of congestion into 3 categories (low, medium and high) for segments and 2 categories for intersections. The stratification of the diagnostic parameters by AADT provides the ability to identify accident patterns more accurately, sharpening the diagnostic tool, so to speak. This improves the effectiveness of decision support. For instance, on two-lane rural roads in flat and rolling terrain in Colorado, the average proportion of overturning crashes is 22.53% in the low range of ADT (0-3,000), 13.68% in the midrange (3,000-8,000) and 11.71% in the high range (>8,000). Similarly for rear-end collisions the average proportion is 2.77% in the low range, 5.92% in the midrange and 10.12% in the high range of ADT (**Table A**). Not accounting for this change may lead to misdiagnosis of problems and potentially construction of ineffective interventions.

Table A. Stratified Diagnostic Norms

Rural Flat and Rolling 2-Lane UnDivided Highways								
Description	0 – 3,000 ADT		3,000 – 8,000 ADT		> 8,000 ADT		All Totals	
	Accidents	Percent	Accidents	Percent	Accidents	Percent	Accidents	Percent
Severity								
PDO	*3,718*	*70.58%*	*3,219*	*75.02%*	*347*	*68.85%*	*7,284*	*72.38%*
INJ	*1,444*	*27.41%*	*1,002*	*23.35%*	*143*	*28.37%*	*2,589*	*25.73%*
FAT	*106*	*2.01%*	*70*	*1.63%*	*14*	*2.78%*	*190*	*1.89%*
Persons Injured	*1,982*	*N/A*	*1,475*	*N/A*	*210*	*N/A*	*3,667*	*N/A*
Persons Killed	*122*	*N/A*	*80*	*N/A*	*15*	*N/A*	*217*	*N/A*
Accident Type								
Overturning	*1,187*	***22.53%***	*587*	***13.68%***	*59*	***11.71%***	*1,833*	*18.22%*
Other Non-Collision	*80*	*1.52%*	*57*	*1.33%*	*8*	*1.59%*	*145*	*1.44%*
Vehicle Cargo/Debris	*63*	*1.20%*	*99*	*2.31%*	*7*	*1.39%*	*169*	*1.68%*
Pedestrian	*7*	*0.13%*	*9*	*0.21%*	*2*	*0.40%*	*18*	*0.18%*
Broadside	*0*	*0.00%*	*0*	*0.00%*	*0*	*0.00%*	*0*	*0.00%*
Head On	*51*	*0.97%*	*81*	*1.89%*	*19*	*3.77%*	*151*	*1.50%*
Rear End	*146*	***2.77%***	*254*	***5.92%***	*51*	***10.12%***	*451*	*4.48%*
Sideswipe (Same Direction)	*55*	*1.04%*	*76*	*1.77%*	*13*	*2.58%*	*144*	*1.43%*
Sideswipe (Opposite Direction)	*126*	*2.39%*	*182*	*4.24%*	*23*	*4.56%*	*331*	*3.29%*

Six years later, Johnson, T. et al in 2009 TRB paper Differences in the Performance of Safety Performance Functions Estimated for Total Crash Count and for Crash Count by Crash Type[5] also objected against assumption of homogeneity in proportions of crashes used in the diagnostic methods. Thru the use of rudimentary SPFs Johnson et al was able to show that homogeneity in proportion assumption does not hold true across the range of AADT. These findings are consistent with 2003 findings of Kononov and Allery[1]. Jonsson et al recommended that the homogeneity-in-proportion assumption be abandoned and crash type models predicting frequency of the crash type should be used to identify locations with elevated number of crashes

[5] Jonsson, T et al, Differences in the Performance of Safety Performance Functions Estimated for Total Crash Count and for Crash Count by Crash Type *in Transportation Research Record 2102*, TRB, National Research Council, Washington, D.C., 2009, pp. 115-123

of specific type. Additionally, Jonsson et al emphasized a benefit of calibrating changes in severity for a specific crash type.

In 2016 FHWA (6) (Srinivasan, Bahar and Gross) published a practical guide on Reliability of Safety Management Methods with focus on Diagnosis. To demonstrate the value of more reliable diagnostic methods, the guide used binomial probability testing of proportion. The guide also emphasized the fact that existence of collision patterns susceptible to correction may or may not be accompanied by excess collisions, initially observed by Kononov[4].

In 2017 Ivan et al[6] conducted an NCHRP study developing Improved Prediction Models for different Crash Types at different facilities, specifically, two-lane rural highways, multilane rural highways, and urban/suburban arterials. The study was based on the understanding that the proportion of crashes by type or severity level may be influenced by traffic volume.

The intent of this project is to compare the effectiveness of network screening and diagnostic methods using aggregate SPFs and Test of Proportions with crash type SPFs. Both methods were applied to the same datasets containing crash history and exposure data. Analysis was restricted to crash types to match crash type-specific SPFs developed under this project, though diagnostic norms for other crash attributes (icy road, dark-unlighted etc.) are well-developed. The following facility types were used; 2-Lane Rural Highways (***3,790 miles***), 4-Lane Urban Freeways (***213 miles***), 4-Lane, 3-Leg, Urban, Divided, Unsignalized Intersections (***176 intersections***) and 4-Lane, 4-Leg, Urban, Divided Signalized Intersections (***189 intersections***).

[6]NCHRP 17-62 Draft Final Report on Improved Prediction Models for Crash Types and Crash Severities, Prepared by Ivan, Persaud, Srinivasan, Abdel-Aty, Lyon, Al Mamun, Lee, Farid, Wang, Lan, Smith, Ravishanker, Prepared for the TRB of the National Academies, June 2017.

DEVELOPMENT OF CRASH TYPE SAFETY PERFORMANCE FUNCTIONS

Segment Dataset Preparation

All of the dataset preparation was performed using the Colorado Department of Transportation (MDT) accident database. Accident history for each facility was prepared over the 5-year period from 1/1/2014 to 12/31/2018. Annual Average Daily Traffic (AADT) for each roadway segment for each of the 5 years was entered into the same dataset; intersection related accidents were removed prior to fitting of the model. Isolating a distance of approximately 250 ft. on both sides of rural intersections is a conservative measure, but it will ensure that intersection related conflicts will not pollute the dataset comprised of non-intersection related accidents on road segments. **Figure 1** illustrates how segment datasets were prepared. For freeways, all of the interchange related accidents including accidents that occurred on ramps and crossroads were removed from the accident database prior to fitting the model. The reason for removing ramp and cross road accidents was to isolate mainline-only crashes required for the development of Freeway crash type SPFs. **Figure 2** illustrates how freeway segment datasets were prepared.

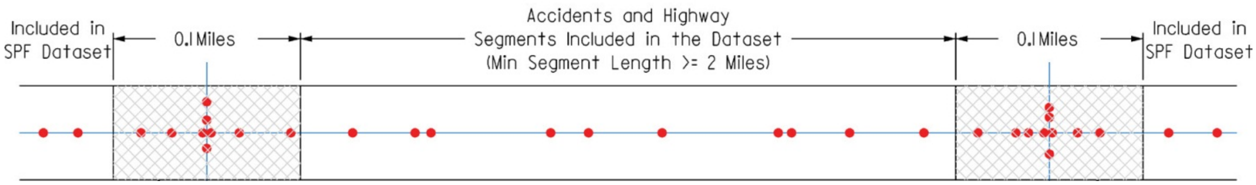

Figure 1. Dataset Preparation for Rural 2-Lane Highways

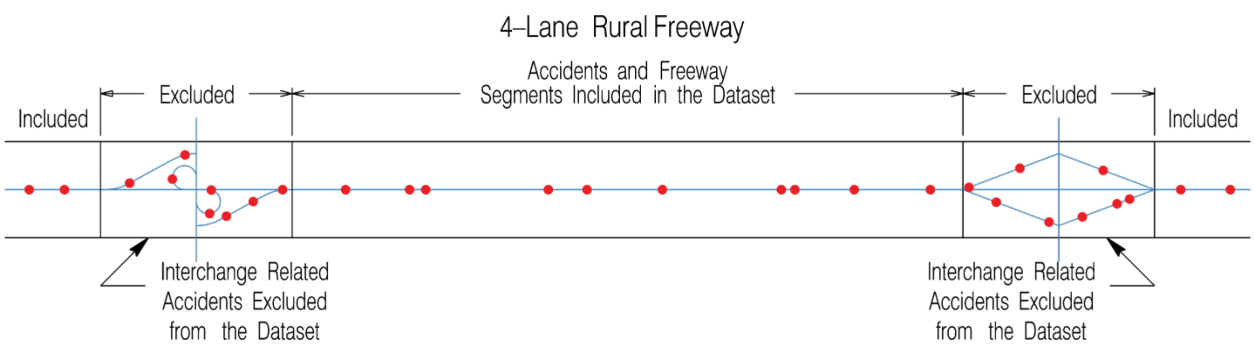

Figure 2. Dataset Model for Urban 4-Lane Interstates

Intersection Dataset Preparation

Intersection and Intersection-related crash history over the study period of 5 years (1/1/2014-12/31/2018) and Annual Average Daily Traffic (AADT) for each intersecting roadway at junctions were entered into the same dataset. All crashes within 150 ft. radius from the center of intersections were considered as intersection or intersection-related, **Figure 3** illustrates how the datasets were prepared.

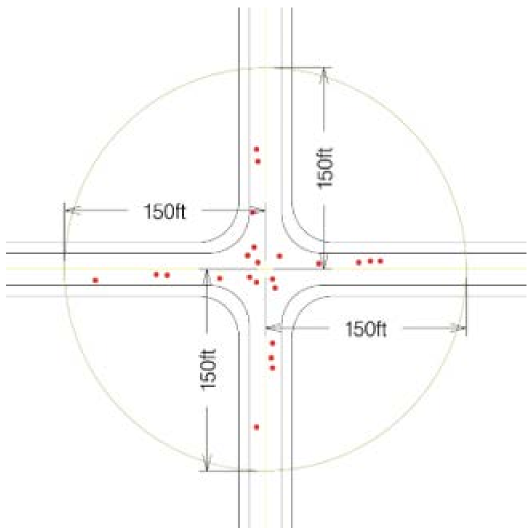

Figure 3. Typical Intersection Dataset Preparation Diagram

Model Development

This project developed selected crash type SPFs for the highway and freeway segments as well as intersections. SPFs in essence are accident prediction models, which generally relate traffic exposure measured in AADT to safety measured in the number of accidents over a unit of time. In statistical modeling of traffic accidents, we are interested in discovering what we can learn about underlying relationships from empirical data containing a random component**.** We suppose that some complex phenomenon manifested by accident occurrence (data generating mechanism) has produced the observations and we wish to describe it by some simpler, but still realistic, model that reveals the nature of the underlying relationship. Lindsey[7] observed that in a model we distinguish between systematic and random variability, where the former describes the

[7] Lindsey, J.K. *Applying Generalized Linear Models*. Springer-Verlag, New York, 1997.

patterns of the phenomenon in which we are particularly interested. A great deal of substantive and comprehensive work in the area of accident modeling was done by Miaou and Lum[8], Hauer and Persaud,[9] Hauer[10] as well as others. The following is a brief description of modeling methodology used in this project using Generalized Linear Models (GLM). Two kinds of Safety Performance Functions were calibrated. The first one addresses the total number of accidents and the second one looks only at accidents involving injury or death. It allows us to assess the magnitude of the specific crash type safety problem from both the frequency and severity standpoints.

Choice of the Model Form

Exploratory data analysis was performed to identify optimal functional form relating dependent and independent variables. Sigmoidal and Hoerl functions, based on substantial empirical evidence derived from observing safety performance of various segments, as well as work of other researchers (Hauer[10]), will be used to represent the underlying relationships between safety and exposure. Sigmoidal and Hoerl functions are both very flexible nonlinear models; they lend themselves well to capturing the overall shape of observed data for the segments and intersections. The general model forms of Sigmoidal and Hoerl functions used in SPF development are provided below:

$E(y) = l\left(\beta_1 + \frac{\beta_2}{1+\beta_3(x^{-\beta_4})}\right)$, Sigmoidal Function for Segment SPFs

$E(y) = l\beta_1(x)^{\beta_2}\exp(\beta_3 x)$, Hoerl Function for Segment SPFs

Where:

$E(y)$ -Number of crashes of a specific type expected to occur annually on a segment of road

x -Segment AADT

l -Segment Length

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[8] Miau S. & Lum H. (1993). Modeling Vehicle Accidents and Highway Geometric Design Relationships. Accident Analysis & Prevention 25(6):689-709.

[9]Hauer, E.& Persaud, B. *Safety Analysis of Roadway Geometric and Ancillary Features*. Transportation Association of Canada 1997.

[10] Hauer, E. (2014). The Art of Regression Modeling in Road Safety. Springer. In press.

β – Model Parameters

$E(x_1, x_2) = \beta_0 + \frac{\beta_1}{(1+\beta_2 x_1{}^{-\beta_3})(1+\beta_4 x_2{}^{-\beta_5})}$, Sigmoidal Function for Intersection SPFs

$E(x_1, x_2) = \beta_0 \left(x_1{}^{\beta_1}\right)\left(x_2{}^{\beta_2}\right)(e^{\beta_3 x_1})$, Hoerl Function for Intersection SPFs

$E(x_1, x_2)$ -Number of crashes of a specific type expected to occur at an intersection given the values of x_1 and x_2

x_1 – AADT Major Road

x_2 – AADT Side Road

β - Model Parameters

Following exploratory data analysis, the Sigmoidal function was selected for the segment crash type SPFs and the Hoerl function was used for the intersection type SPFs.

Model Fitting and Goodness of Fit

The model parameters were estimated by the maximum-likelihood method using Generalized Linear Modeling (GLM) methodology by maximizing log-likelihood function. Maximizing log-likelihood function has computational advantages over maximizing ordinary likelihood function L, which represent the product of the individual probability density functions of Poisson or Negative Binomial distributions. All datasets exhibited over-dispersion, and as a result, final regression parameters for crash type SPFs were estimated by maximizing log-likelihood function of the Negative Binomial distribution, details are shown below.

$E(y) = \mu$

$Var(y) = \mu(1 + \alpha\mu) = \mu + \alpha\mu^2 > \mu$, thus, the standard deviation of y is $\sqrt{\mu + \alpha\mu^2}$

$L(\mu, \alpha) = \prod_{i=1}^{n} \frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!} \left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right)^{y_i} \left(\frac{1}{1+\alpha\mu_i}\right)^{\alpha^{-1}}$

$\ln\left(L(\mu, \alpha)\right) = \sum_{i=1}^{n} \ln\left(\frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!}\right) + y_i \ln\left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right) + \alpha^{-1} \ln\left(\frac{1}{1+\alpha\mu_i}\right)$

Where:

y – vector of random variables modeling annual accident counts on segments or intersections

μ – expected values of y, estimated by the SPF

y_i – observed number of accidents on a segment or intersection over one year, a sample from the i^th^ component of y.

α – scalar over-dispersion parameter

$L(\mu, \alpha)$ – Negative Binomial likelihood function

Γ – Gamma Function

The quality of fit was confirmed with the Cumulative Residuals (CURE) method described in Hauer and Bamfo[11]. The CURE method displays visually how well the fitted model function describes the data set. To generate a CURE plot, sites are sorted by their average AADT. Then, for each site, the residual (observed accidents- predicted accidents) is computed. The k^{th} cumulative residual is calculated by summing first k residuals. The cumulative residuals are plotted against the corresponding AADT. Because of the random nature of accident counts, the cumulative residual line represents a so-called 'random walk'. For a model that fits well in all ranges of AADT, the cumulative residual plot should oscillate around zero. If the cumulative residual value steadily increases within a range of values of the independent variable, then, within that range, the model predicts fewer accidents than have been observed. Similarly, a decreasing cumulative residual line indicates that, in that range, fewer accidents have been observed than are predicted by the model. The cumulative residual line for a model that fits the data well should lie largely within two standard deviations of a theoretical random walk. Failure to do so indicates the presence of outliers or signifies an ill-fitting model. For example, **Figure 4** shows a CURE plots reflecting a very acceptable model fit for broadside crashes at urban 4-leg, 4-lane, divided, signalized intersections. Because the CURE residual line lies well within the two standard deviation and generally oscillates around zero, it can be concluded that the functional form and the model parameters fit the data well. All CURE plots reflecting severity and frequency models of crash type SPFs developed under this project show a very acceptable fit, with the exception of the wild animal crashes, which are always difficult to predict.

[11] Hauer, E., and J. Bamfo. Two Tools for Finding What Function Links the Dependent Variable to the Explanatory Variables. *Proc., International Cooperation on Theories and Concepts in Traffic Conference,* Lund, Sweden, November 1997.

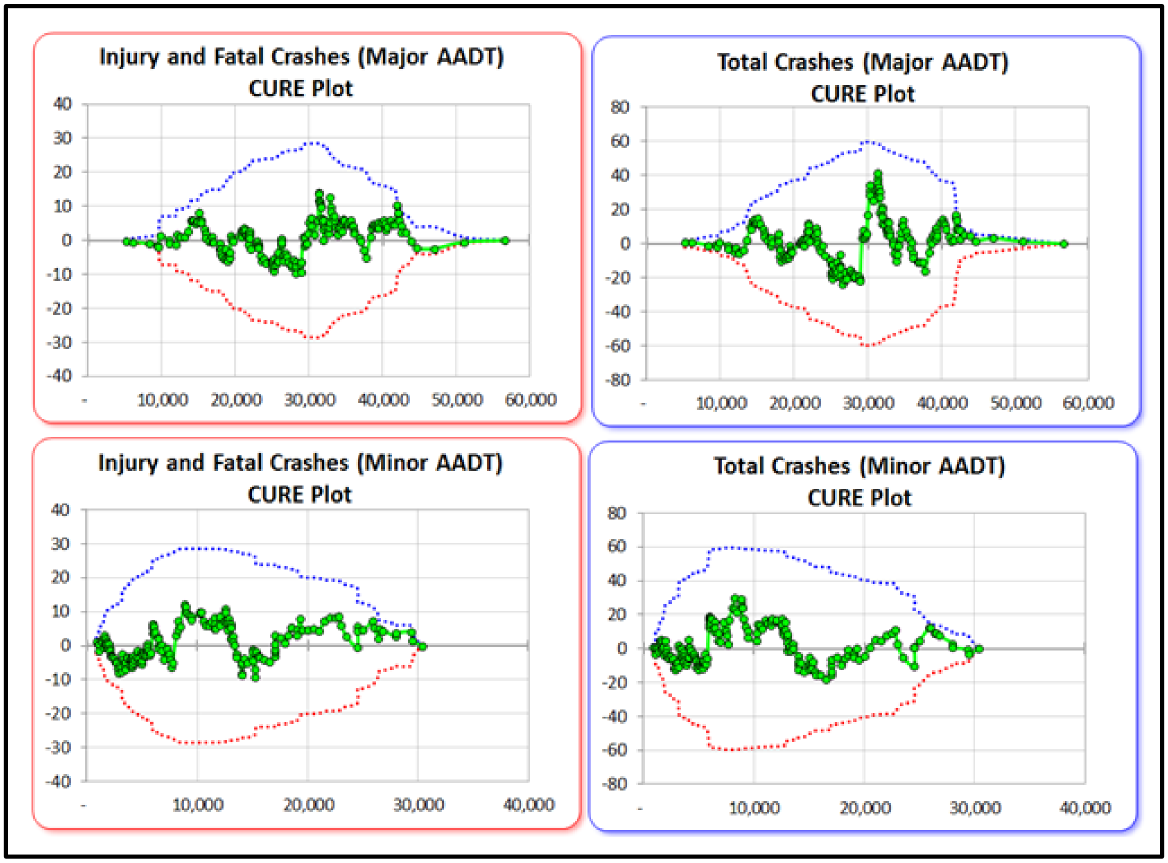

Figure 4. 4-Leg Divided Urban Signalized Intersection Broadside Crashes SPF and CURE Plots for Major and Minor ADT

Crash Type SPFs were developed for the following facilities:

Urban 4-Lane Divided Signalized 4-Leg Intersections (Rear End, Broadside, Approach Turn, Sideswipe Same)

Urban 4-Lane Divided Unsignalized 3-Leg Intersections (Rear End, Broadside, Approach Turn, Sideswipe Same)

Rural Flat and Rolling 2-Lane Undivided Highways (Wild Animal, Fixed Objects, Overturns, Rear-ends)

Urban 4-Lane Freeways (Rear-end, Sideswipe Same, Fixed Objects Overturns)

Model parameters for segments and intersections with related crash types are summarized in **Table B**.

Table B. Model Parameters for Crash Type SPFs

Urban 4-Lane Divided Signalized 4-Leg Intersections (Hoerl Function) - 189 Intersections

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	-1.24E+01	8.18E-01	6.33E-01	2.57E-02	3.00E+00	3.34E-01	-1.40E+01	1.16E+00	6.19E-01	-9.44E-02	4.23E+00	2.36E-01
Broadside	-2.56E+01	2.49E+00	3.76E-01	-8.13E-01	3.66E+00	2.73E-01	-1.90E+01	1.96E+00	2.94E-01	-5.94E-01	4.81E+00	2.08E-01
Approach Turn	-2.11E+01	2.37E+00	1.63E-03	-6.57E-01	1.09E+00	9.21E-01	-1.47E+01	1.67E+00	8.97E-02	-3.51E-01	1.61E+00	6.21E-01
Sideswipe (Same)	-7.21E+00	-2.77E-01	9.17E-01	1.81E-01	1.21E+02	8.25E-03	-1.00E+01	3.94E-01	7.93E-01	9.28E-02	3.62E+00	2.76E-01

Urban 4-Lane Divided Unsignalized 3-Leg Intersections (Hoerl Function) - 176 Intersections

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	1.00E-03	-3.58E-01	1.24E-01	7.89E-01	1.18E+00	8.48E-01	1.00E-03	-2.03E-01	1.19E-01	7.09E-01	1.39E+00	7.20E-01
Broadside	-2.44E+01	2.55E+00	7.33E-02	-9.46E-01	8.60E+00	1.16E-01	-6.71E+00	6.76E-01	1.01E-01	-7.32E-02	1.43E+00	6.98E-01
Approach Turn	1.82E-01	-6.29E-01	3.85E-01	8.23E-01	1.10E+00	9.09E-01	-3.97E+00	1.06E-02	3.60E-01	4.07E-01	1.16E+00	8.62E-01
Sideswipe (Same)	1.00E-03	-4.21E-01	1.29E-01	-1.17E-01	1.61E+01	6.22E-02	1.00E-03	-2.78E-01	9.52E-02	4.82E-01	1.87E+00	5.35E-01

Rural 2-Lane Undivided Highways (Sigmoid Function) - 3,971 Segments Totalling 3,790 Miles

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Wild Animal	6.71E-01	1.49E+00	8.36E+03	1.77E-02	8.17E-01	1.22E+00	8.01E+00	1.44E+00	6.72E+03	9.05E-02	7.02E-01	1.42E+00
Fixed Objects	7.44E+02	8.76E-01	1.45E+07	7.47E-03	2.02E+00	4.96E-01	1.04E+01	1.12E+00	1.51E+04	4.97E-02	1.80E+00	5.55E-01
Overturns	9.59E+01	6.67E-01	1.40E+07	2.76E-02	2.39E+00	4.19E-01	3.37E+00	9.18E-01	1.45E+04	9.30E-02	2.54E+00	3.94E-01
Rear End	1.03E+01	1.75E+00	4.70E+04	1.96E-03	2.15E+00	4.66E-01	2.77E+01	1.79E+00	4.70E+04	6.61E-03	2.36E+00	4.24E-01

Urban 4-Lane Freeways (Sigmoid Function) - 230 Segments Totalling 213 Miles

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	6.10E+01	3.07E+00	8.36E+04	1.00E-03	4.87E+00	2.05E-01	1.70E+02	3.56E+00	7.81E+04	3.70E-01	5.37E+00	1.86E-01
Sideswipe (Same)	9.84E+00	2.12E+00	8.36E+04	1.00E-03	5.75E+00	1.74E-01	3.30E+01	2.94E+00	6.10E+04	1.04E+00	5.95E+00	1.68E-01
Fixed Objects	1.67E+01	1.35E+00	8.36E+04	0.00E+00	5.21E+00	1.92E-01	6.05E+01	1.38E+00	8.36E+04	1.00E+00	6.33E+00	1.58E-01
Overturns	5.31E+00	9.26E-01	6.46E+04	0.00E+00	6.68E+00	1.50E-01	5.00E+00	1.62E+00	6.46E+04	1.71E+00	5.71E+00	1.75E-01

Urban 4-Lane Divided Signalized 4-Leg Intersections (Hoerl Function) - 189 Intersections

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	-1.24E+01	8.18E-01	6.33E-01	2.57E-02	3.00E+00	3.34E-01	-1.40E+01	1.16E+00	6.19E-01	-9.44E-02	4.23E+00	2.36E-01
Broadside	-2.56E+01	2.49E+00	3.76E-01	-8.13E-01	3.66E+00	2.73E-01	-1.90E+01	1.96E+00	2.94E-01	-5.94E-01	4.81E+00	2.08E-01
Approach Turn	-2.11E+01	2.37E+00	1.63E-03	-6.57E-01	1.09E+00	9.21E-01	-1.47E+01	1.67E+00	8.97E-02	-3.51E-01	1.61E+00	6.21E-01
Sideswipe (Same)	-7.21E+00	-2.77E-01	9.17E-01	1.81E-01	1.21E+02	8.25E-03	-1.00E+01	3.94E-01	7.93E-01	9.28E-02	3.62E+00	2.76E-01

Urban 4-Lane Divided Unsignalized 3-Leg Intersections (Hoerl Function) - 176 Intersections

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	1.00E-03	-3.58E-01	1.24E-01	7.89E-01	1.18E+00	8.48E-01	1.00E-03	-2.03E-01	1.19E-01	7.09E-01	1.39E+00	7.20E-01
Broadside	-2.44E+01	2.55E+00	7.33E-02	-9.46E-01	8.60E+00	1.16E-01	-6.71E+00	6.76E-01	1.01E-01	-7.32E-02	1.43E+00	6.98E-01
Approach Turn	1.82E-01	-6.29E-01	3.85E-01	8.23E-01	1.10E+00	9.09E-01	-3.97E+00	1.06E-02	3.60E-01	4.07E-01	1.16E+00	8.62E-01
Sideswipe (Same)	1.00E-03	-4.21E-01	1.29E-01	-1.17E-01	1.61E+01	6.22E-02	1.00E-03	-2.78E-01	9.52E-02	4.82E-01	1.87E+00	5.35E-01

Rural 2-Lane Undivided Highways (Sigmoid Function) - 3,971 Segments Totalling 3,790 Miles

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Wild Animal	6.71E-01	1.49E+00	8.36E+03	1.77E-02	8.17E-01	1.22E+00	8.01E+00	1.44E+00	6.72E+03	9.05E-02	7.02E-01	1.42E+00
Fixed Objects	7.44E+02	8.76E-01	1.45E+07	7.47E-03	2.02E+00	4.96E-01	1.04E+01	1.12E+00	1.51E+04	4.97E-02	1.80E+00	5.55E-01
Overturns	9.59E+01	6.67E-01	1.40E+07	2.76E-02	2.39E+00	4.19E-01	3.37E+00	9.18E-01	1.45E+04	9.30E-02	2.54E+00	3.94E-01
Rear End	1.03E+01	1.75E+00	4.70E+04	1.96E-03	2.15E+00	4.66E-01	2.77E+01	1.79E+00	4.70E+04	6.61E-03	2.36E+00	4.24E-01

Urban 4-Lane Freeways (Sigmoid Function) - 230 Segments Totalling 213 Miles

	Severity β1	Severity β2	Severity β3	Severity β4	Severity Disp	Severity α	Frequency β1	Frequency β2	Frequency β3	Frequency β4	Frequency Disp	Frequency α
Rear End	6.10E+01	3.07E+00	8.36E+04	1.00E-03	4.87E+00	2.05E-01	1.70E+02	3.56E+00	7.81E+04	3.70E-01	5.37E+00	1.86E-01
Sideswipe (Same)	9.84E+00	2.12E+00	8.36E+04	1.00E-03	5.75E+00	1.74E-01	3.30E+01	2.94E+00	6.10E+04	1.04E+00	5.95E+00	1.68E-01
Fixed Objects	1.67E+01	1.35E+00	8.36E+04	0.00E+00	5.21E+00	1.92E-01	6.05E+01	1.38E+00	8.36E+04	1.00E+00	6.33E+00	1.58E-01
Overturns	5.31E+00	9.26E-01	6.46E+04	0.00E+00	6.68E+00	1.50E-01	5.00E+00	1.62E+00	6.46E+04	1.71E+00	5.71E+00	1.75E-01

Three-dimensional crash type SPF graphs for intersections and two-dimensional graphs for segments with their related CURE plots and equations with model parameters are provided in **Figures 5-100.**

Urban 4-Lane Divided Signalized 4-Leg Intersections, Rear End Collisions

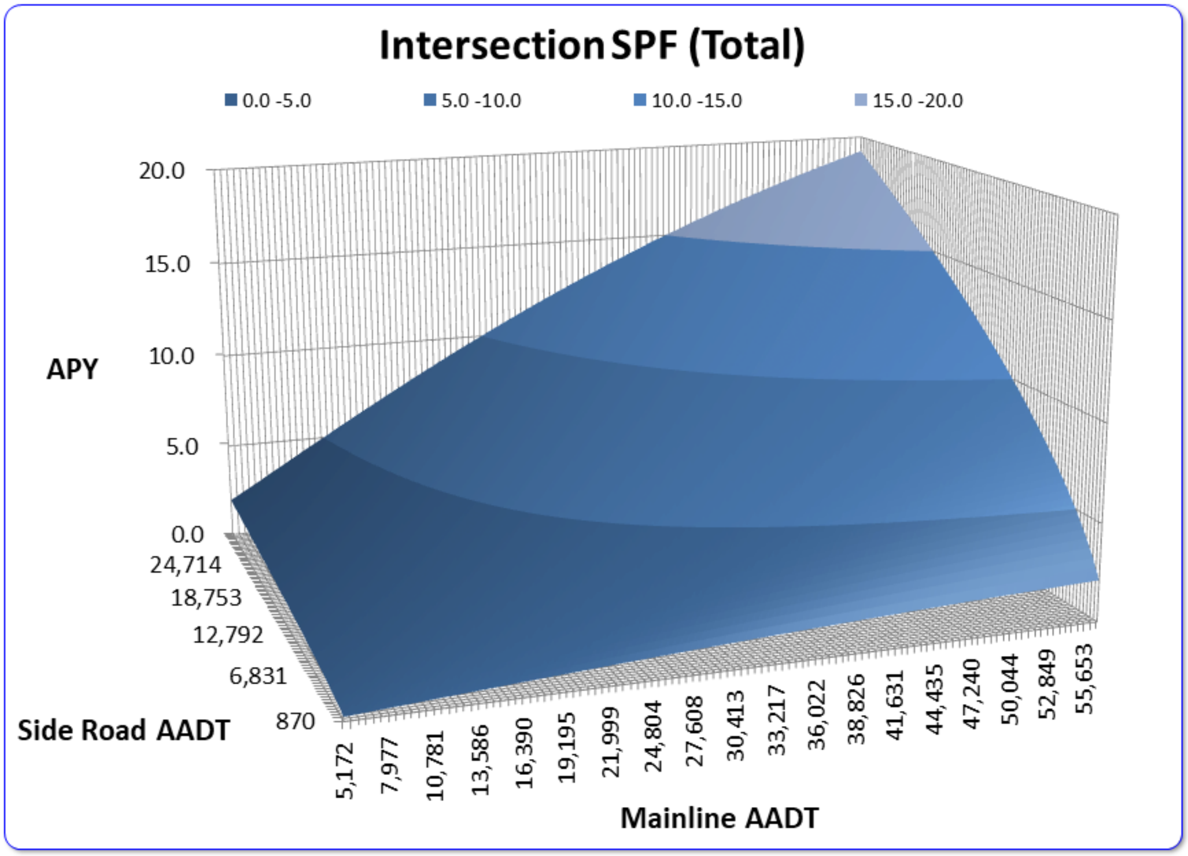

Figure 5. SPF – Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Total Model

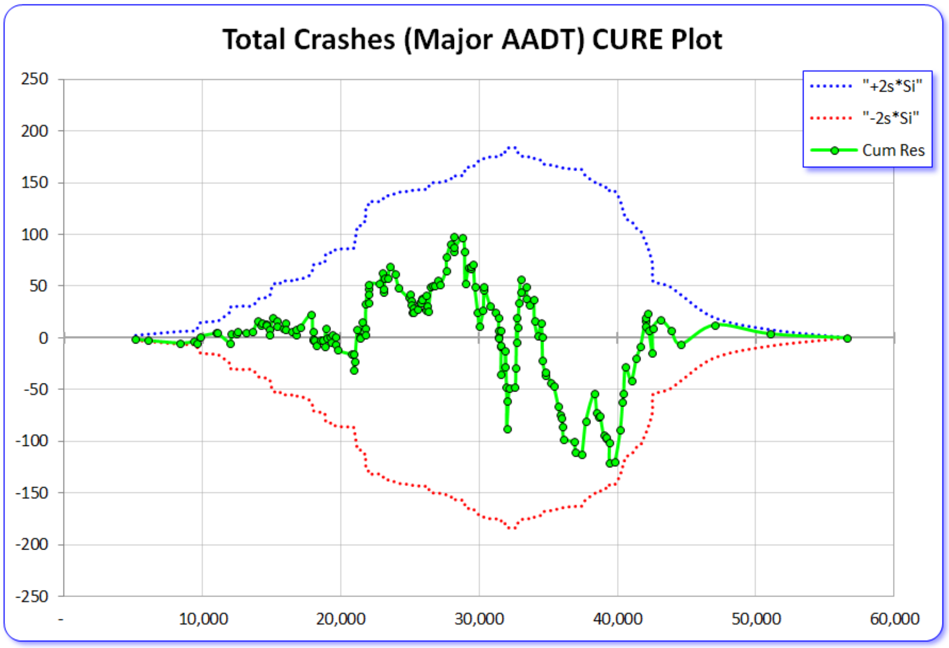

Figure 6. CURE Plot SPF (Major AADT) - Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Total Model

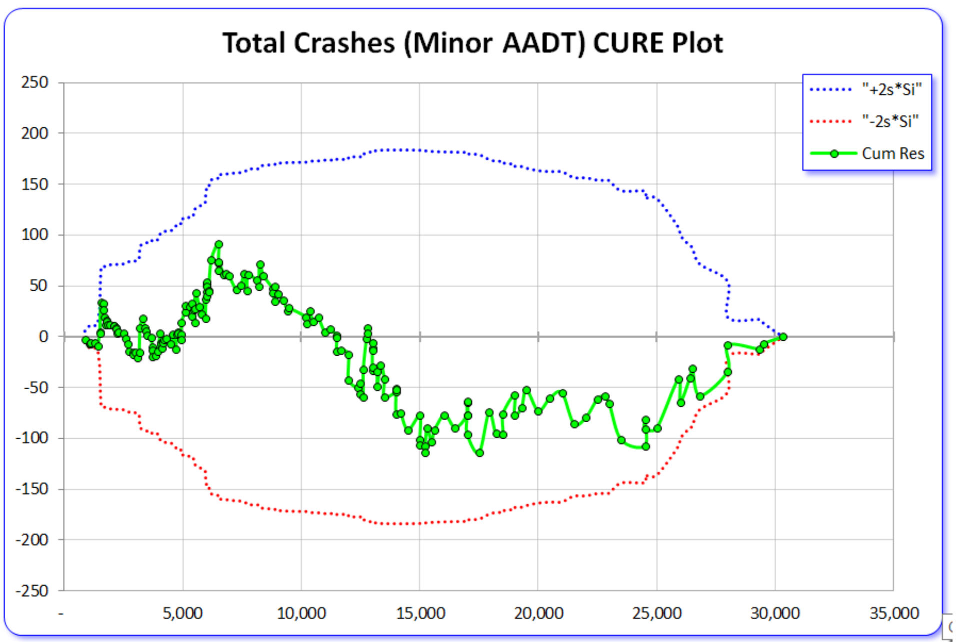

Figure 7. CURE Plot SPF (Minor AADT) - Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Total Model

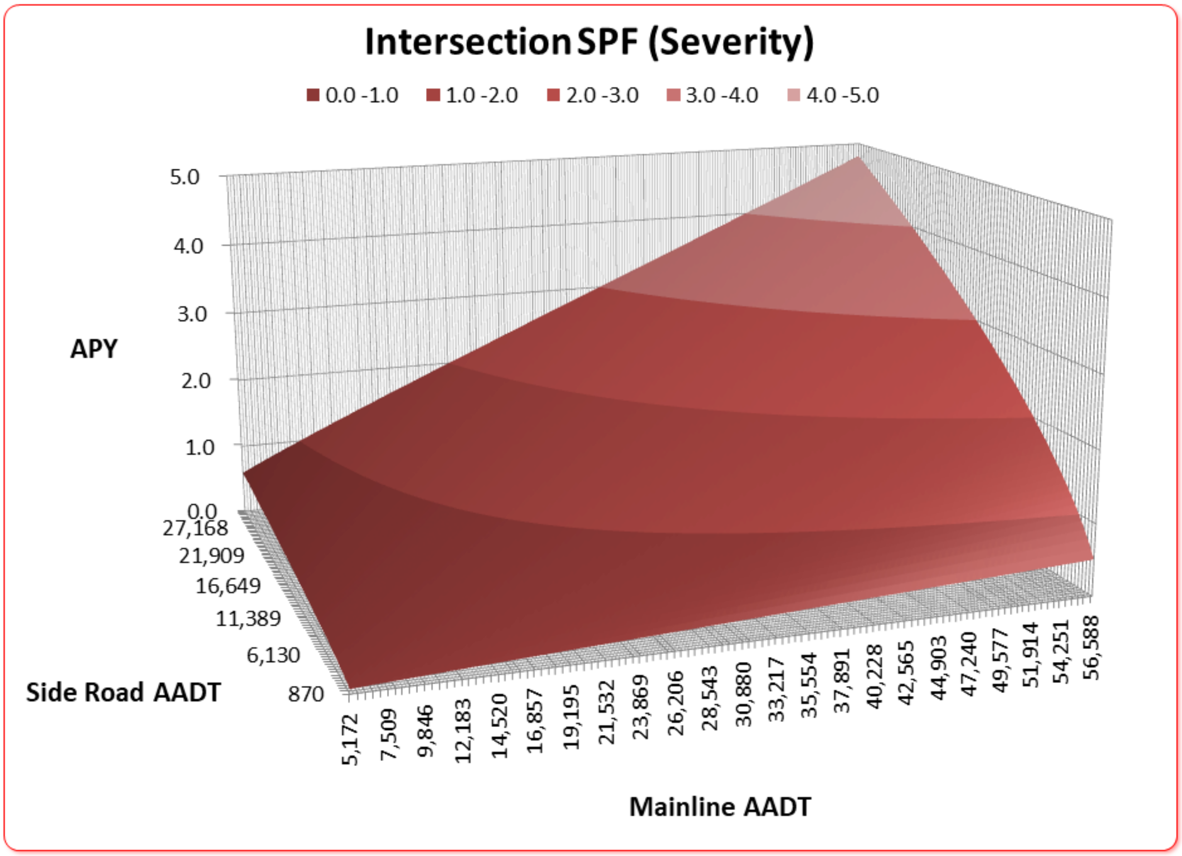

Figure 8. SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Severity Model

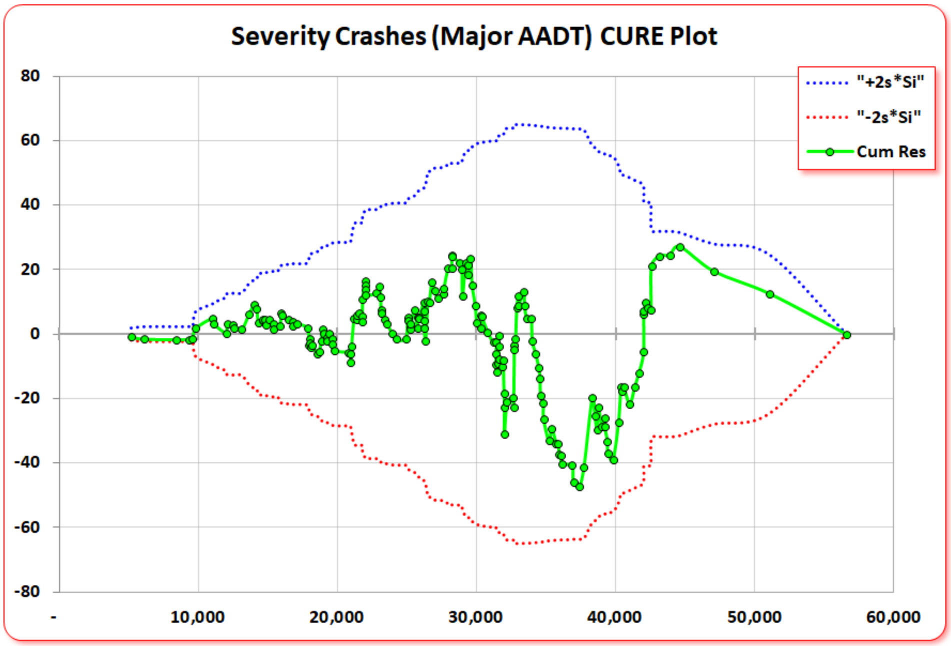

Figure 9. CURE Plot SPF (Major AADT) - Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Severity Model

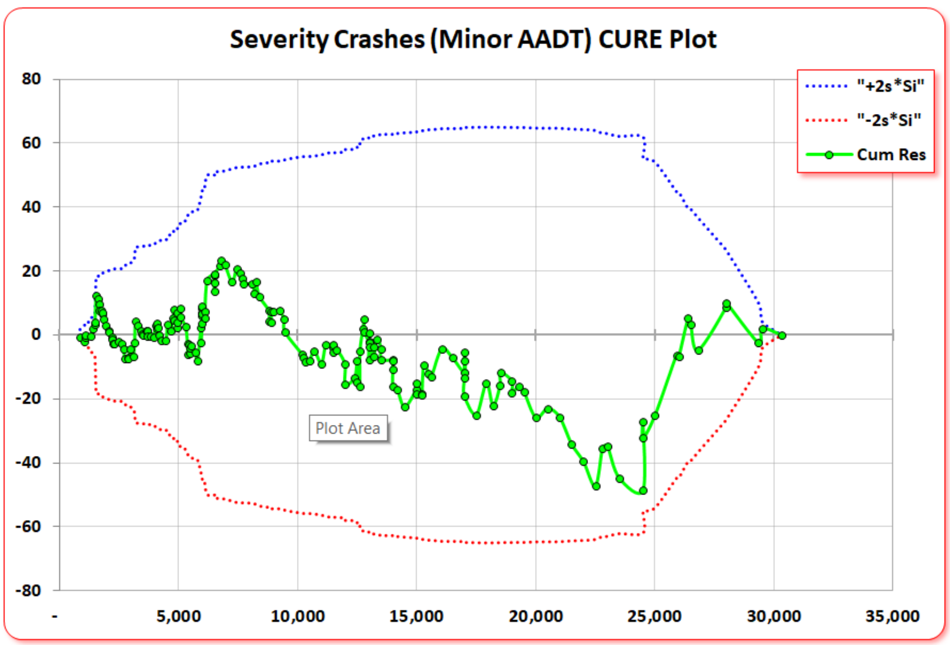

Figure 10. CURE Plot SPF (Minor AADT) - Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	-1.3959E+01
β_2	1.577E+00
β_3	6.1886E-01
β_4	-9.4412E-02
α	2.3616E-01

Severity	
Variable	**Value**
β_1	-1.2449E+01
β_2	8.1823E-01
β_3	6.3261E-01
β_4	2.5664E-02
α	3.3365E-01

Figure 11. SPF Model Parameters, Urban 4-Lane Divided Signalized 4-Leg Intersections – Rear End Collisions

Urban 4-Lane Divided Signalized 4-Leg Intersections, Approach Turn Crashes

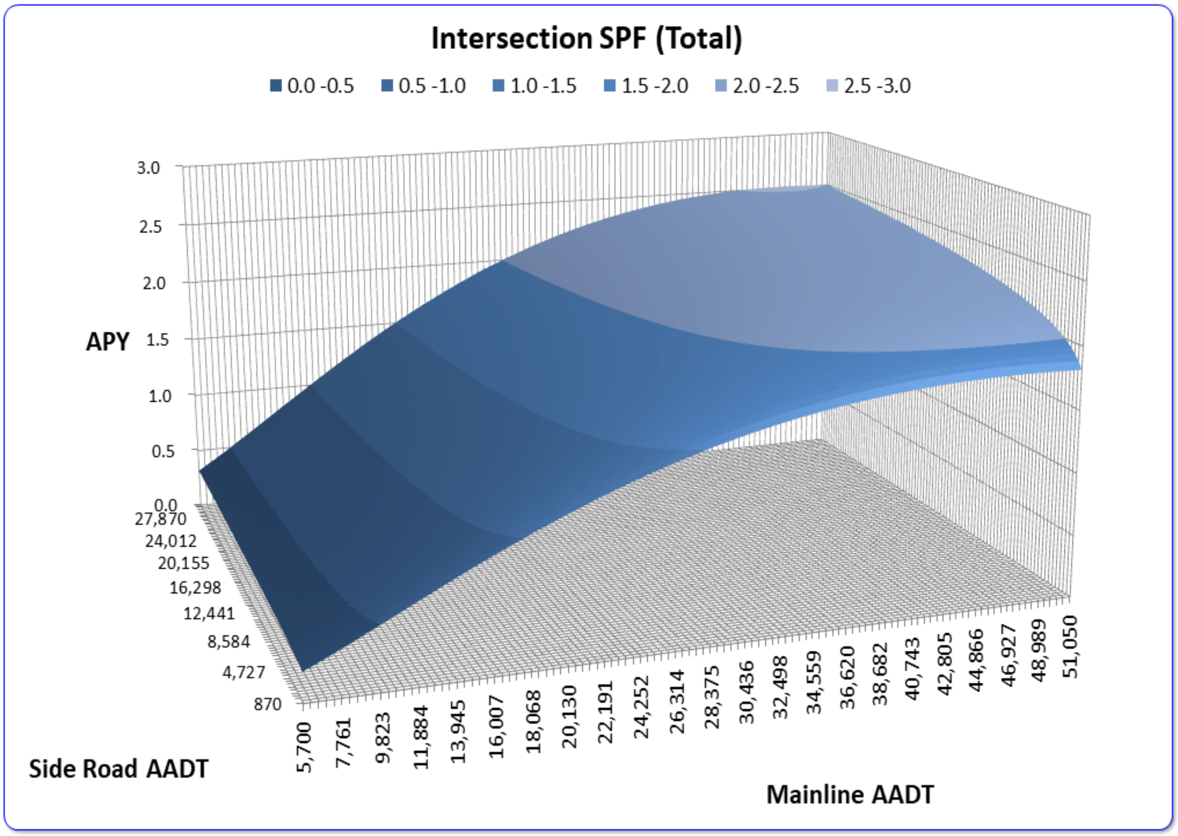

Figure 12. SPF – Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Total Model

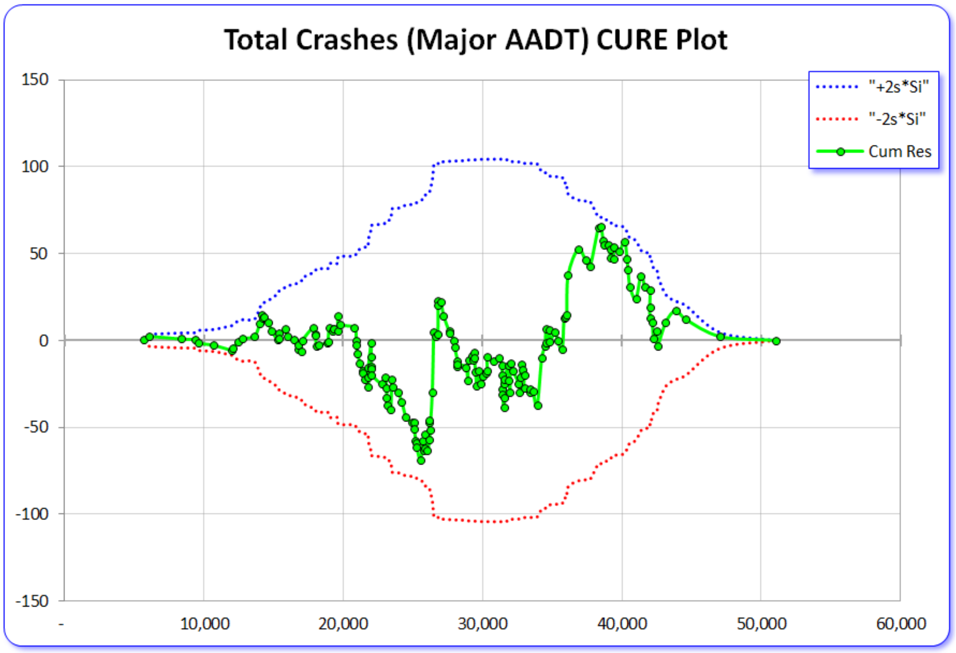

Figure 13. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Total Model

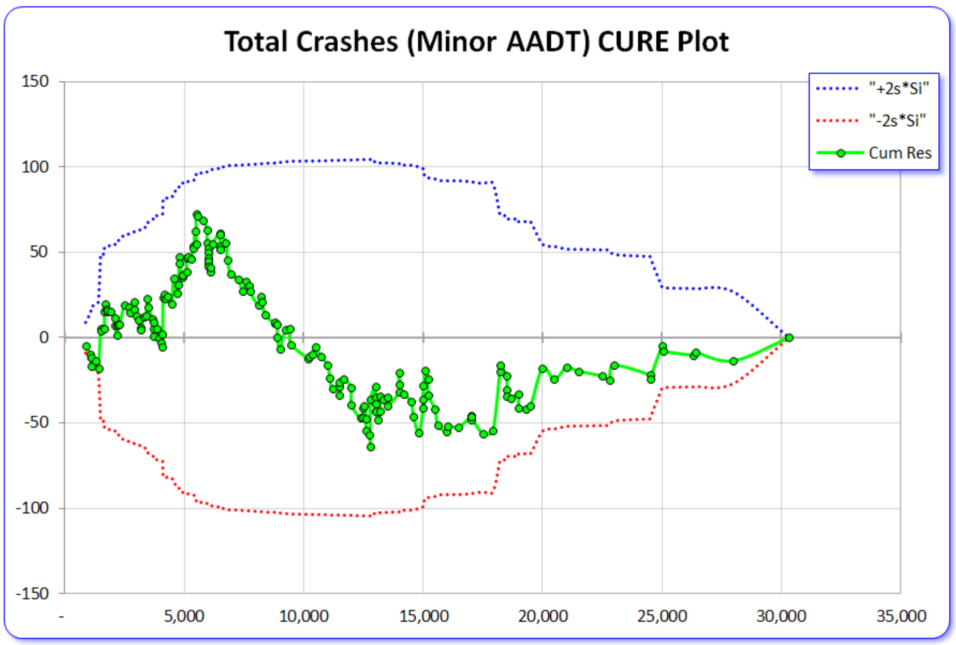

Figure 14. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Total Model

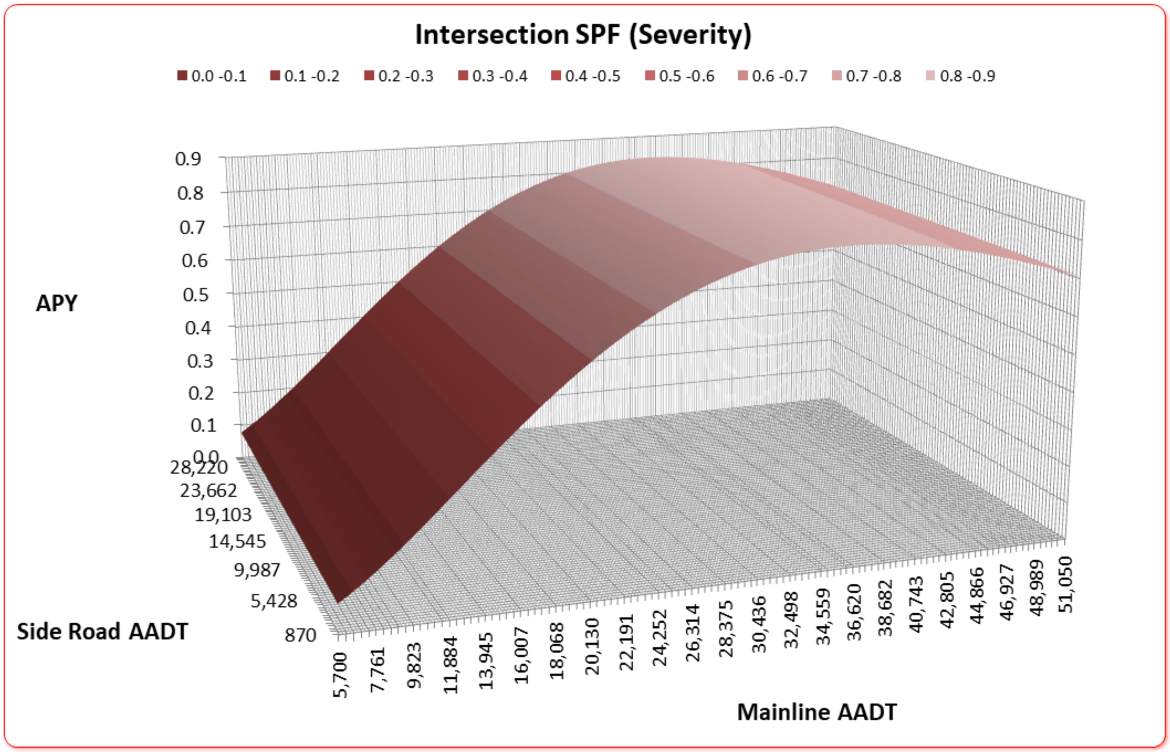

Figure 15. SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Severity Model

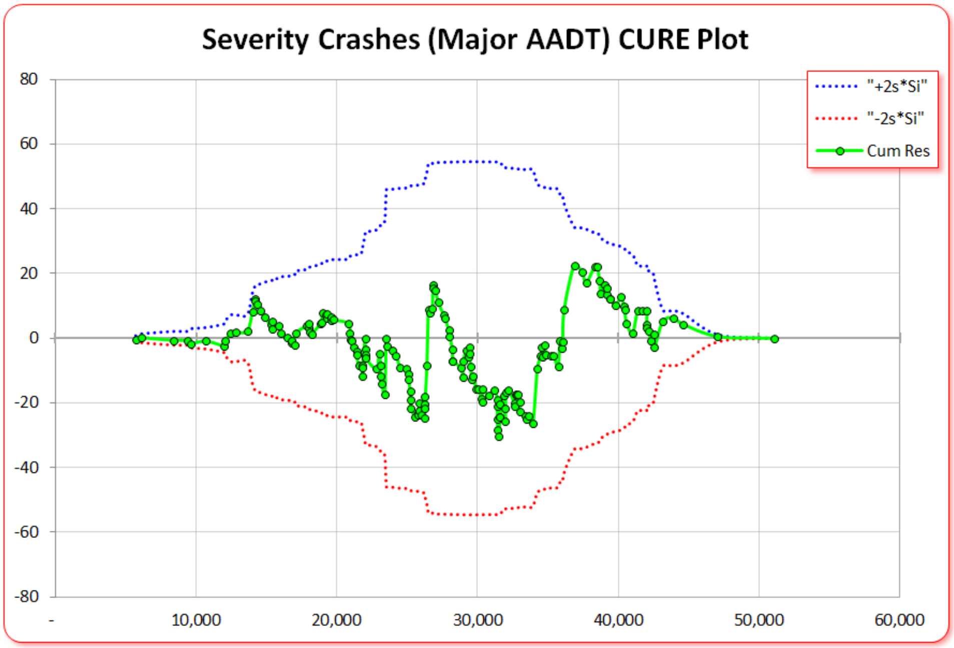

Figure 16. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Severity Model

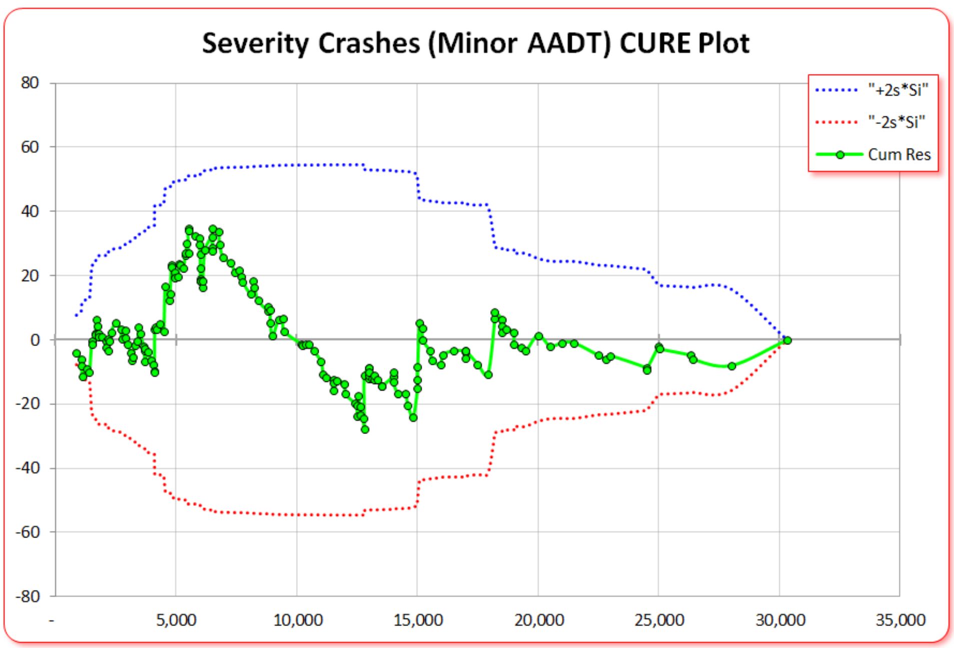

Figure 17. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	-1.4699E+01
β_2	1.6690E+00
β_3	8.9693E-02
β_4	-3.5149E-01
α	6.2133E-01

Severity	
Variable	**Value**
β_1	-2.1100E+01
β_2	2.3712E+00
β_3	1.6330E-03
β_4	-6.5745E-01
α	9.2126E-01

Figure 18. SPF Model Parameters, Urban 4-Lane Divided Signalized 4-Leg Intersections – Approach Turn Crashes

Urban 4-Lane Divided Signalized 4-Leg Intersections, Broadside Crashes

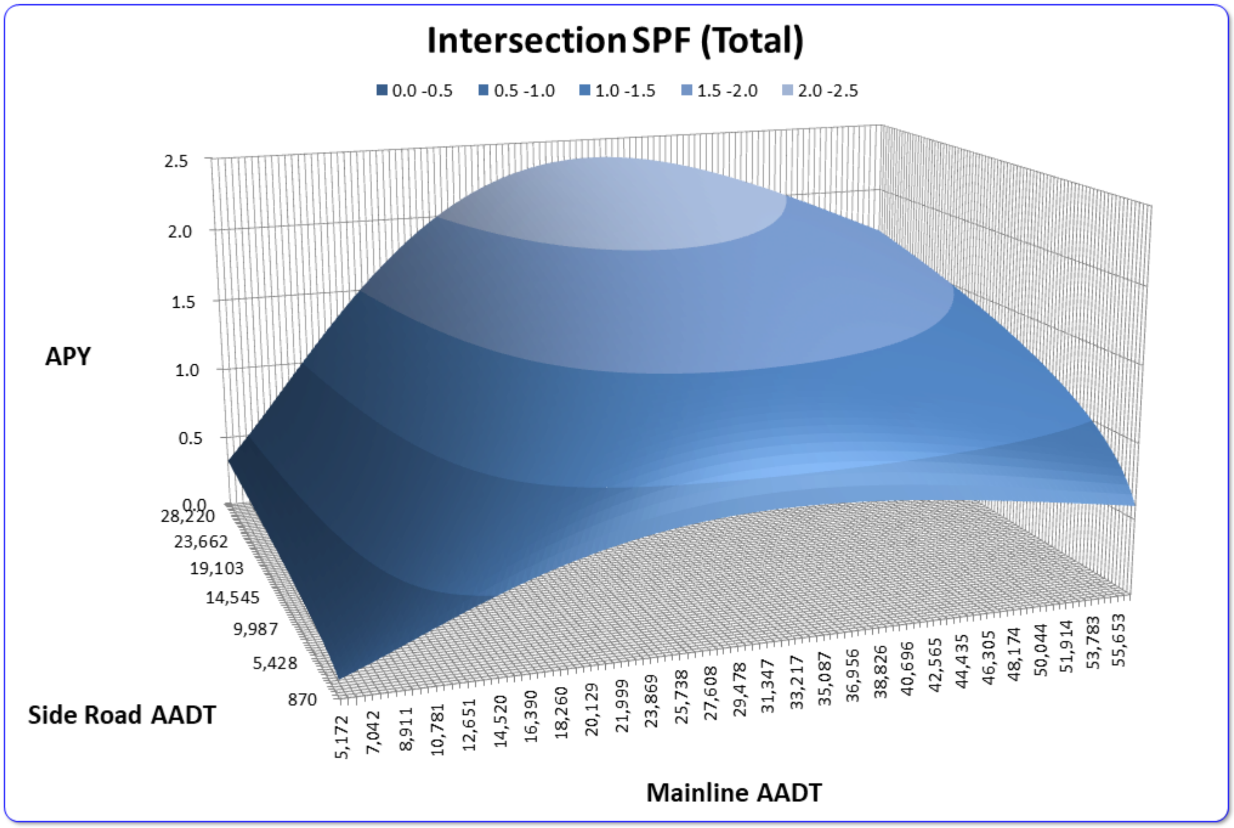

Figure 19. SPF – Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Total Model

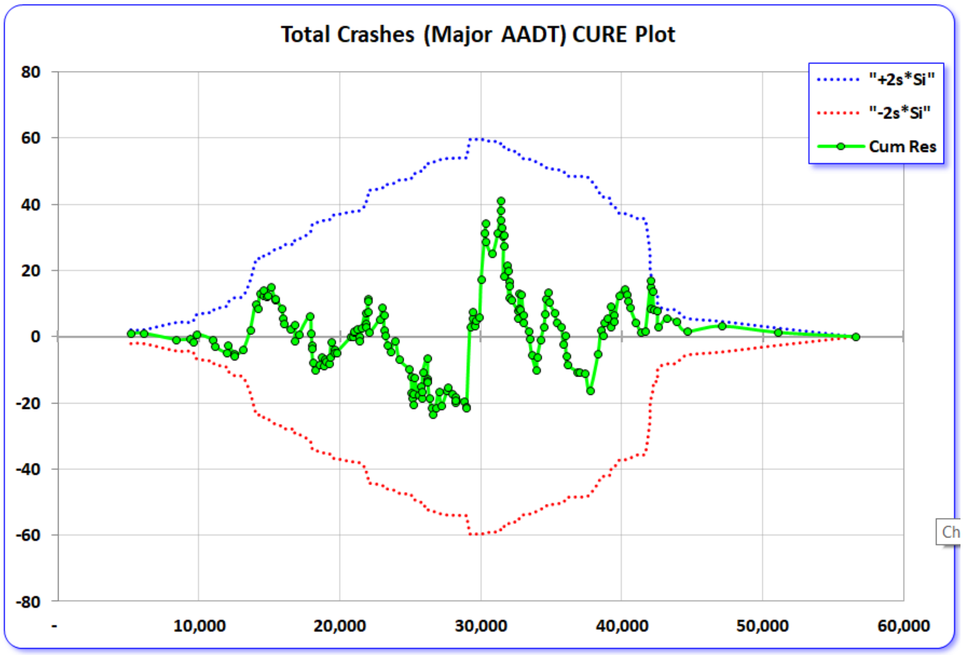

Figure 20. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Total Model

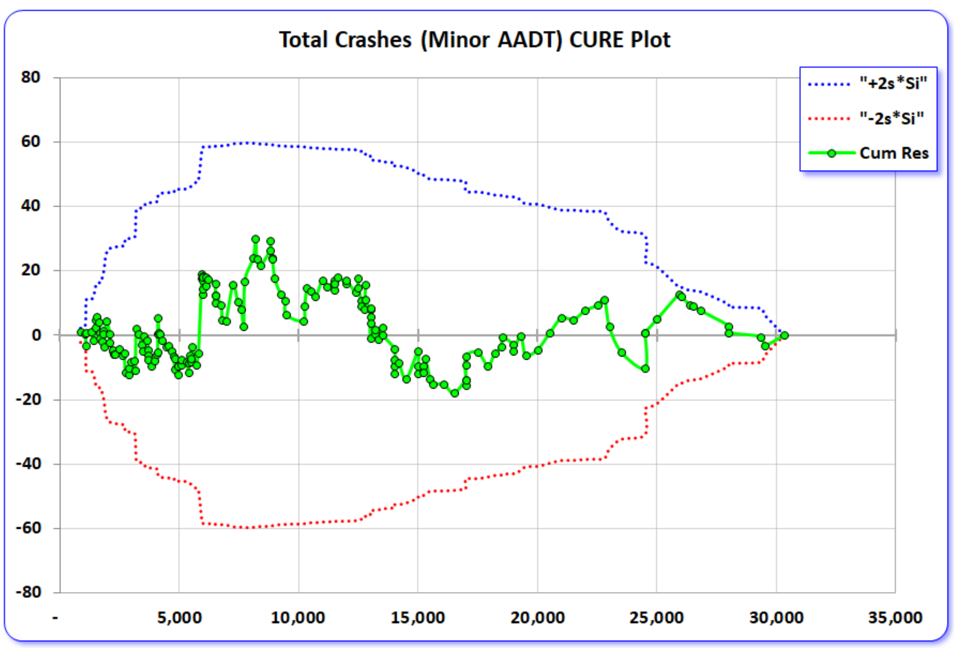

Figure 21. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Total Model

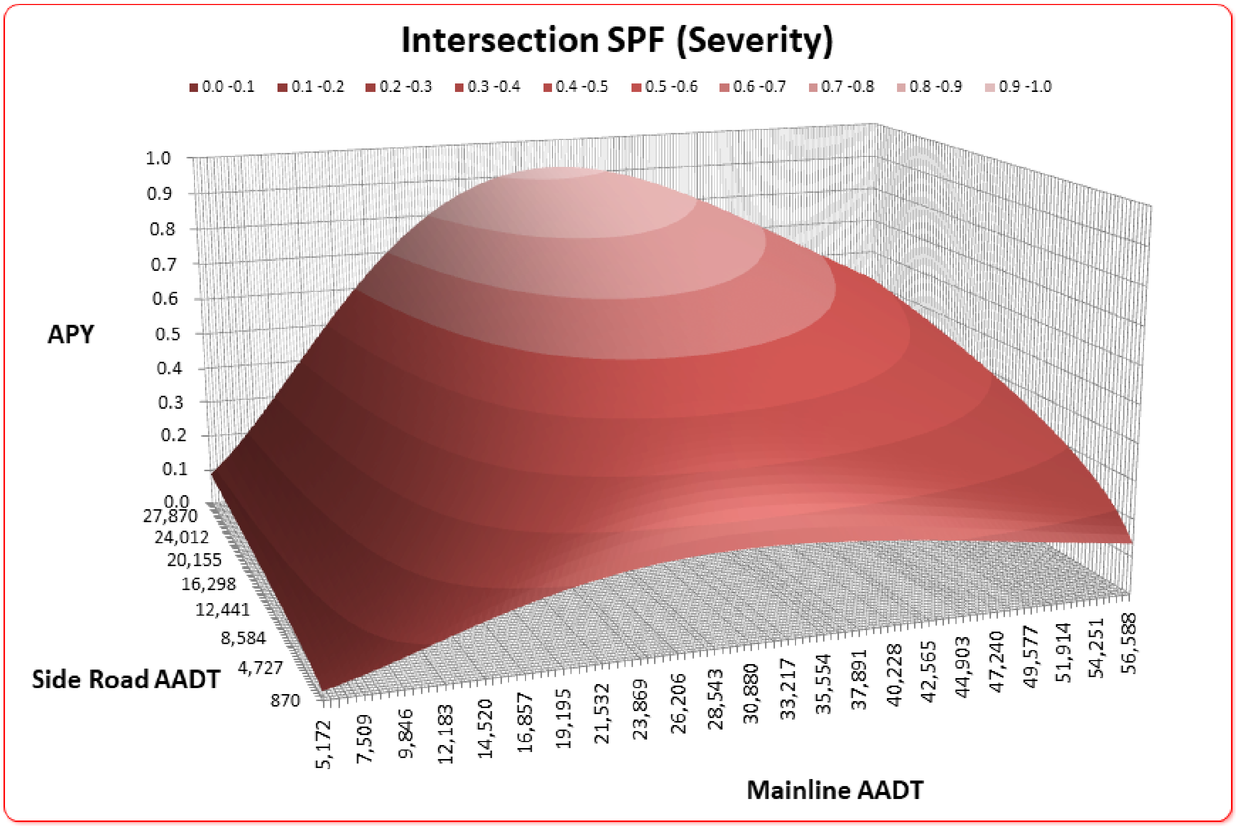

Figure 22. SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Severity Model

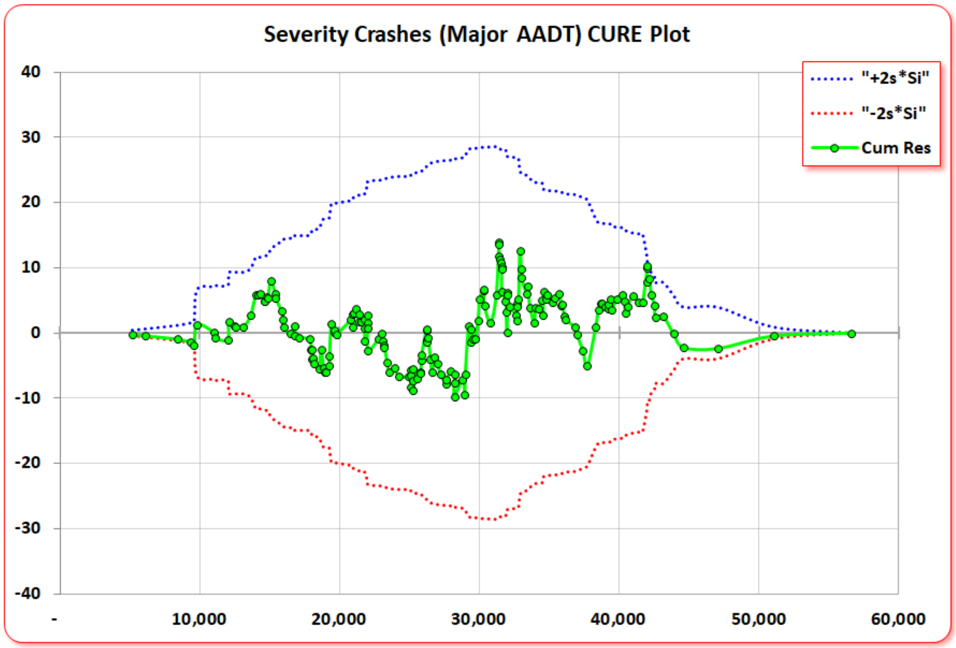

Figure 23. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Severity Model

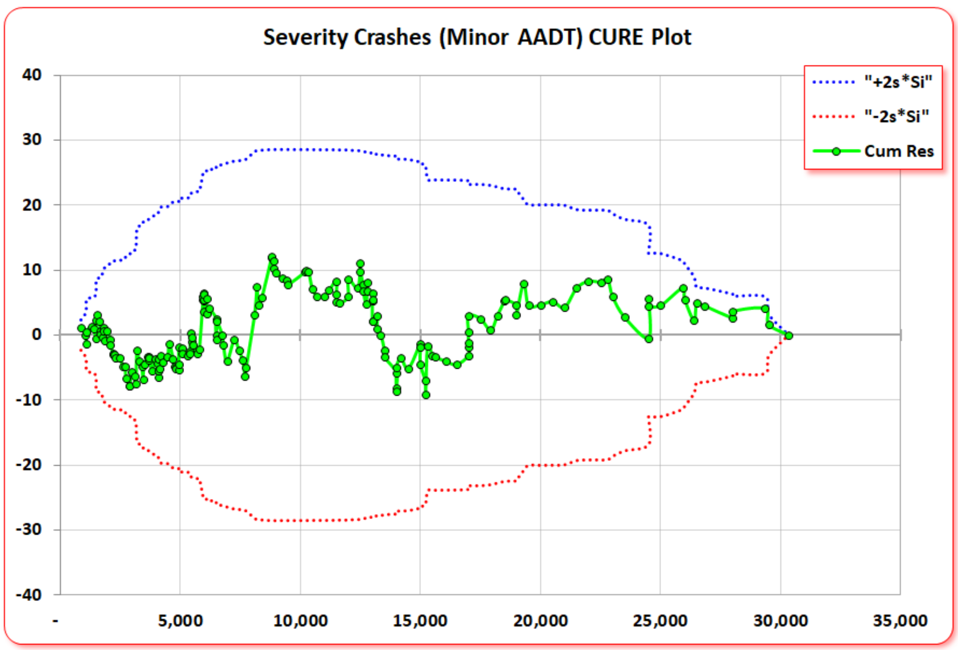

Figure 24. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	-1.8991E+01
β_2	1.9591E+00
β_3	2.9943E-01
β_4	-5.9369E-01
α	2.0788E-01

Severity	
Variable	**Value**
β_1	-2.5633E+01
β_2	2.94943E+00
β_3	3.7624E-01
β_4	-8.1278E-01
α	2.7315E-01

Figure 25. SPF Model Parameters, Urban 4-Lane Divided Signalized 4-Leg Intersections – Broadside Crashes

Urban 4-Lane Divided Signalized 4-Leg Intersections, Same Direction Sideswipes

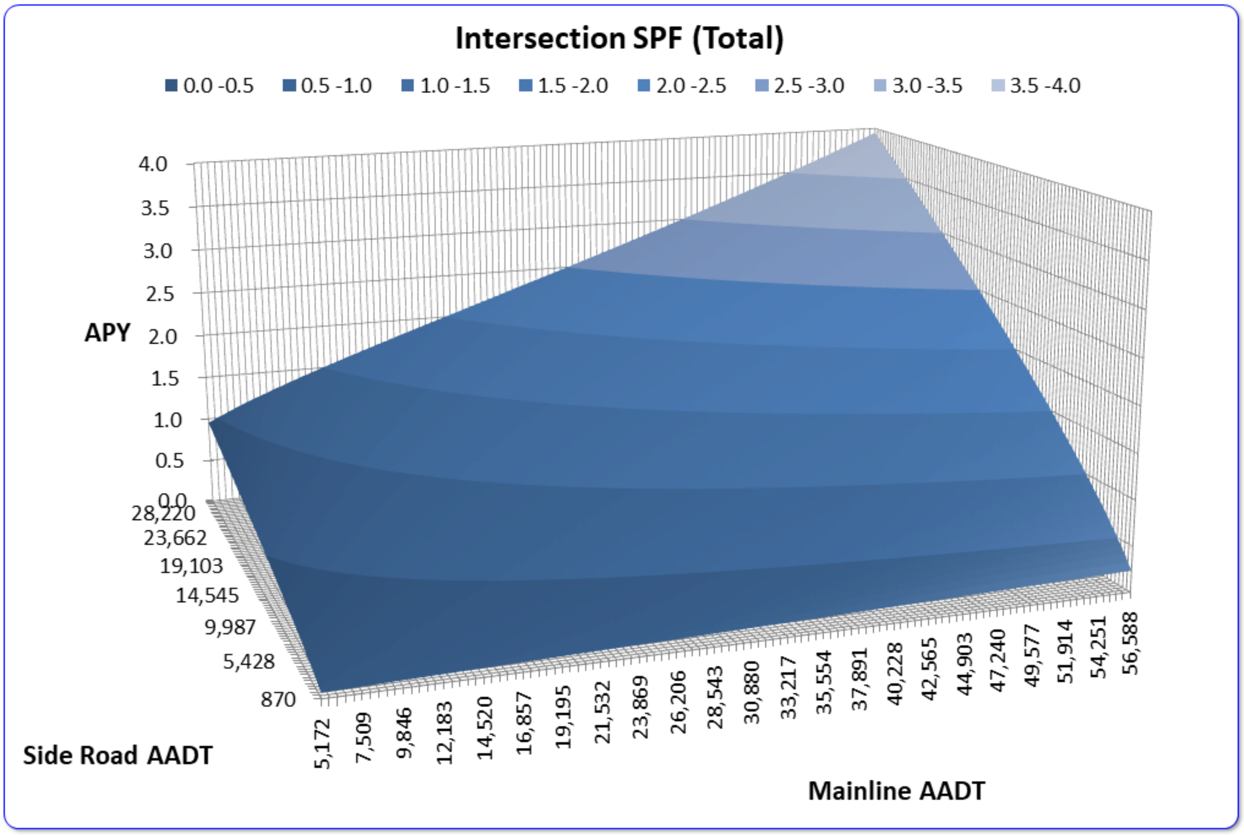

Figure 26. SPF – Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Total Model

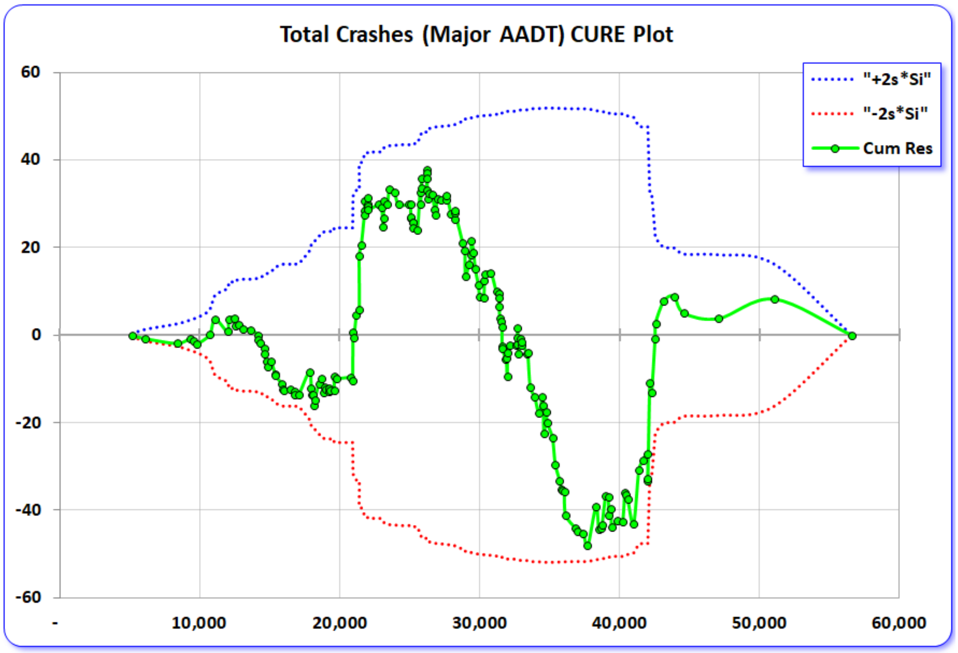

Figure 27. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Total Model

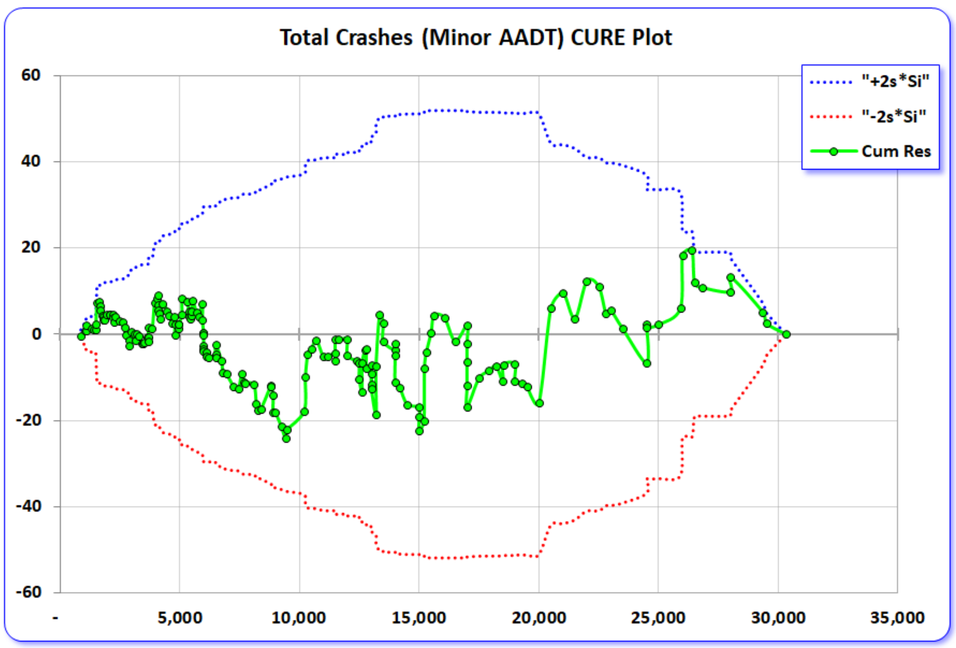

Figure 28. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Total Model

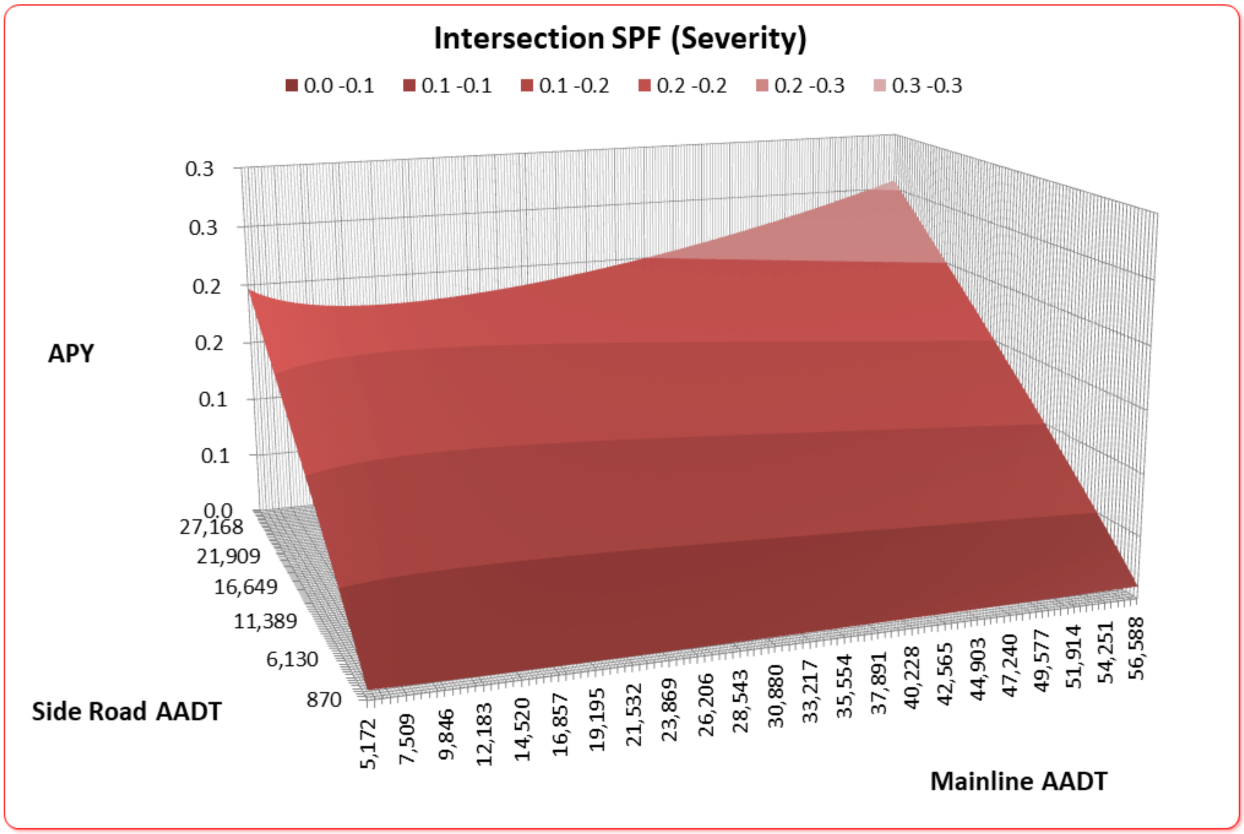

Figure 29. SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Severity Model

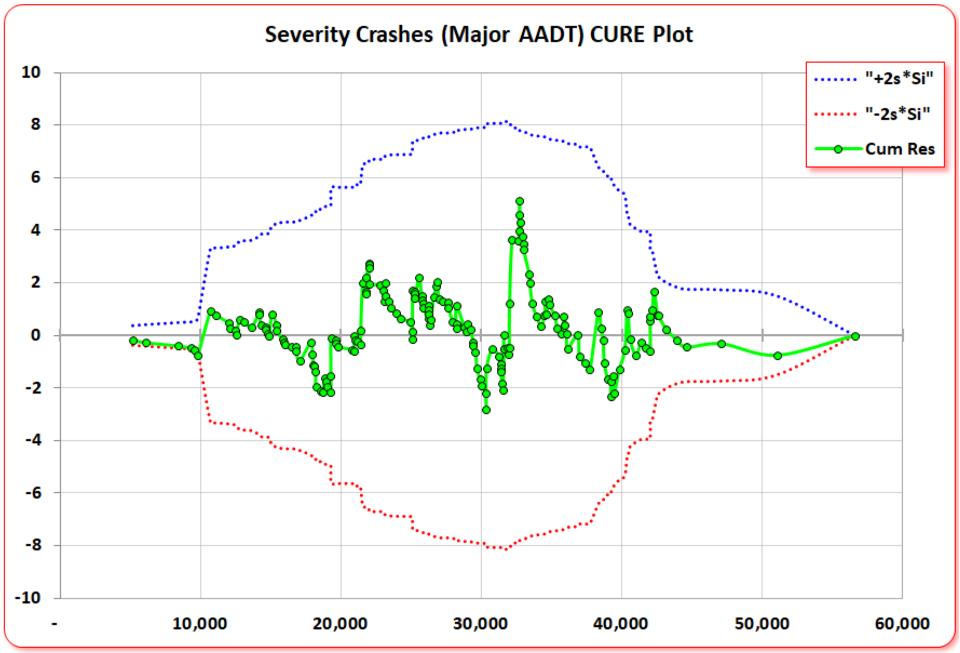

Figure 30. Figure 30 CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Severity Model

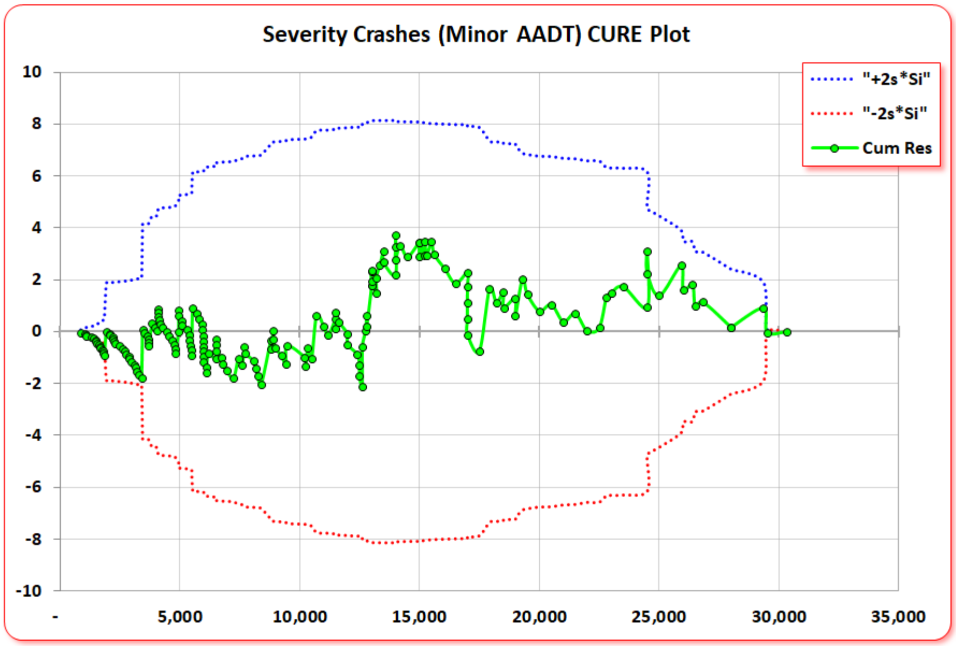

Figure 31. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	-1.0044E+01
β_2	3.9395E-01
β_3	7.9347E-01
β_4	9.2777E-02
α	2.7618E-01

Severity	
Variable	**Value**
β_1	-7.2140E+00
β_2	2.7656E-01
β_3	9.1740E-01
β_4	1.8100E-01
α	8.2465E-01

Figure 32. SPF Model Parameters, Urban 4-Lane Divided Signalized 4-Leg Intersections – Same Direction Sideswipes

Urban 4-Lane Divided Unsignalized 3-Leg Intersections, Rear End Collisions

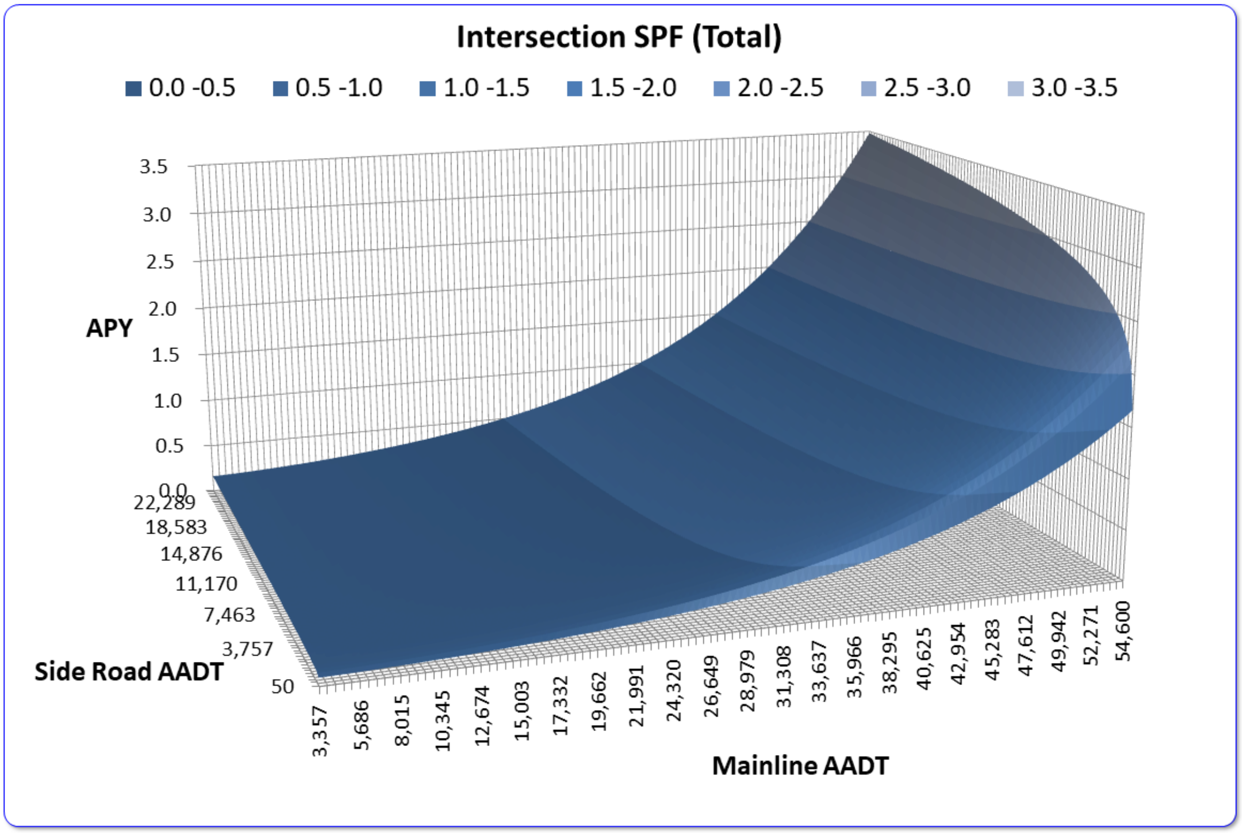

Figure 33. SPF – Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Total Model

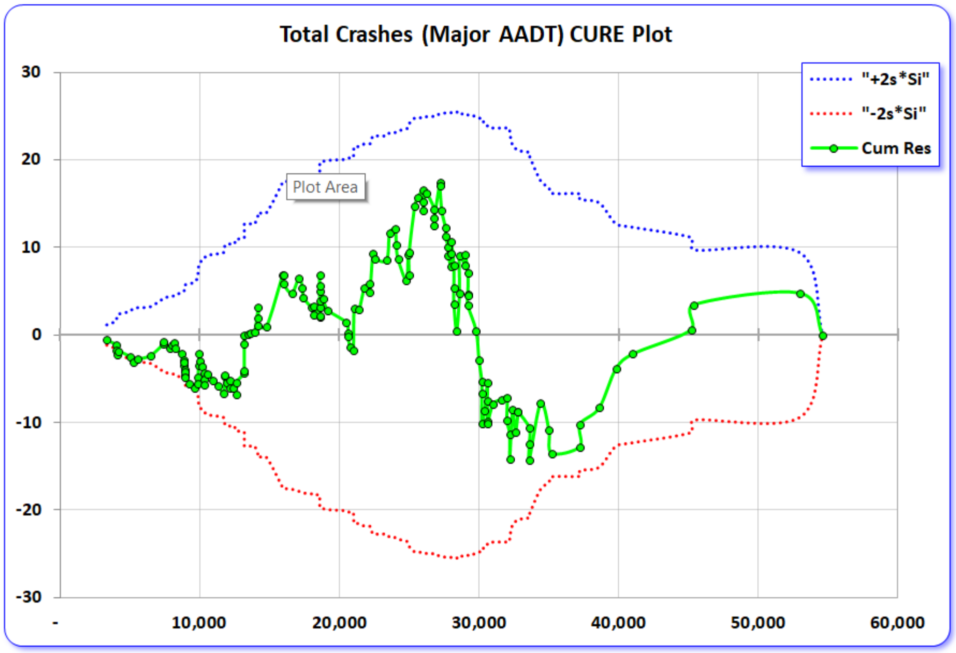

Figure 34. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Total Model

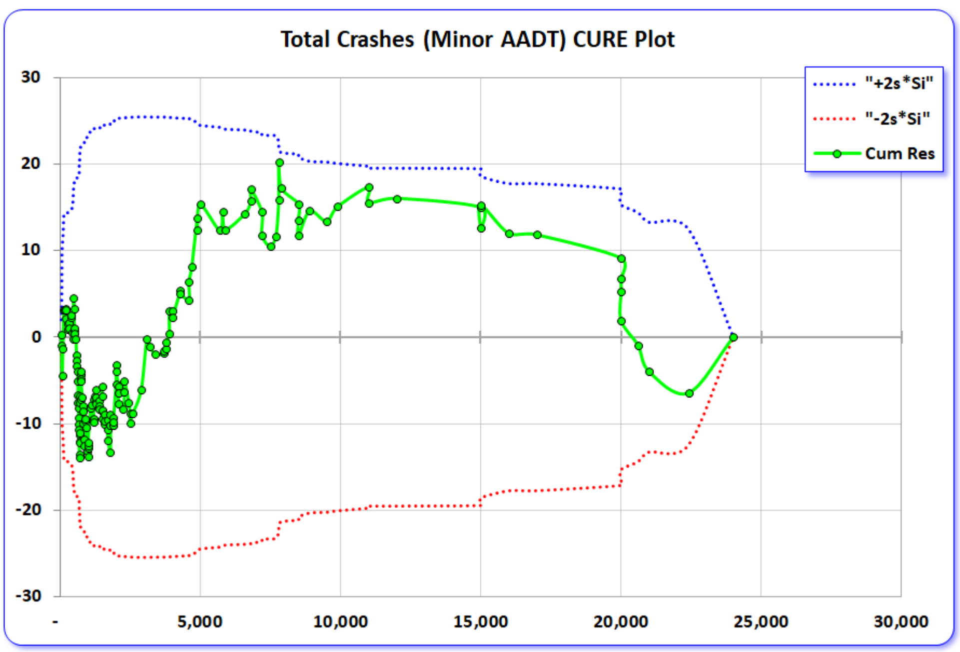

Figure 35. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Total Model

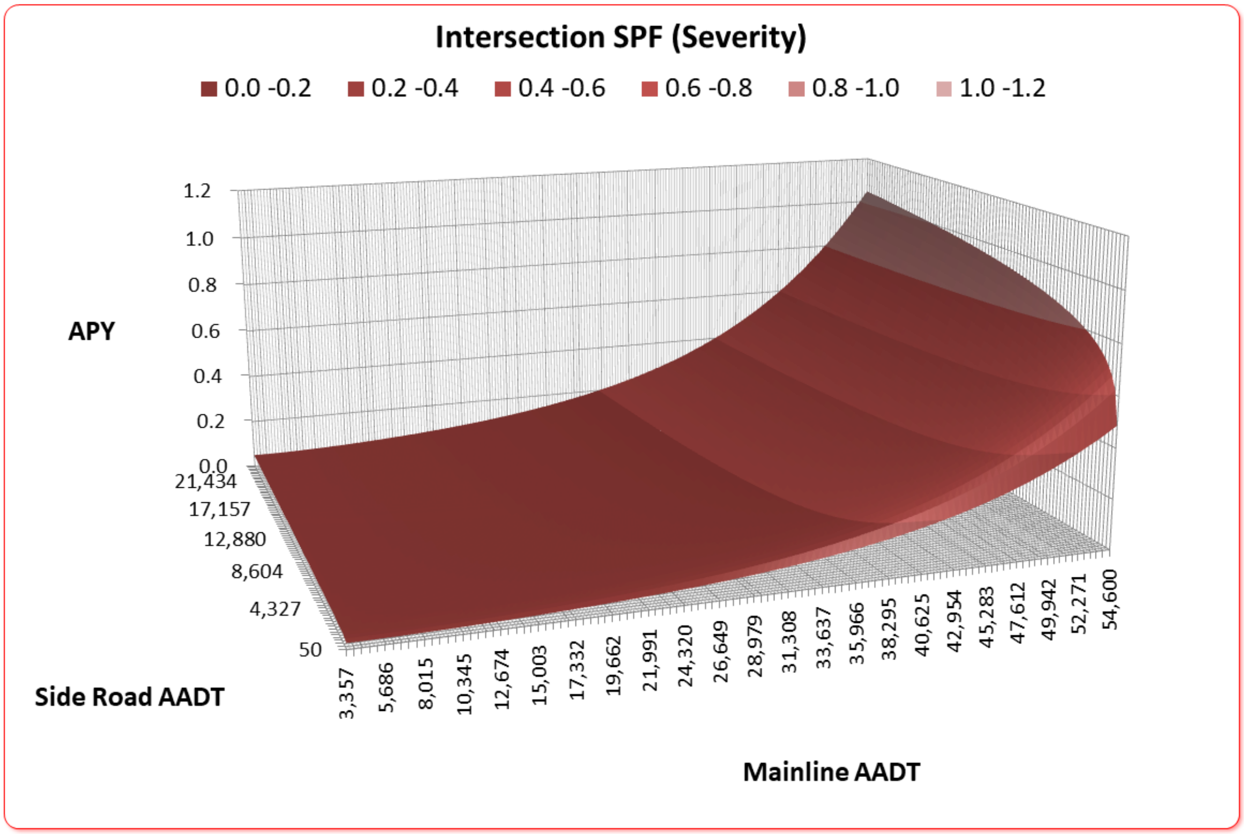

Figure 36. SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Severity Model

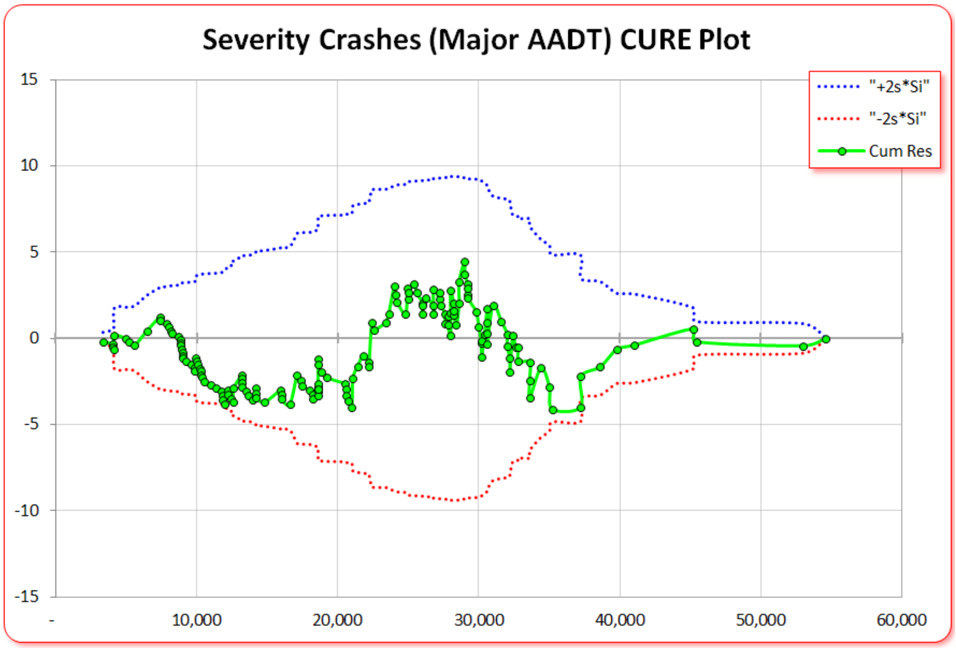

Figure 37. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Severity Model

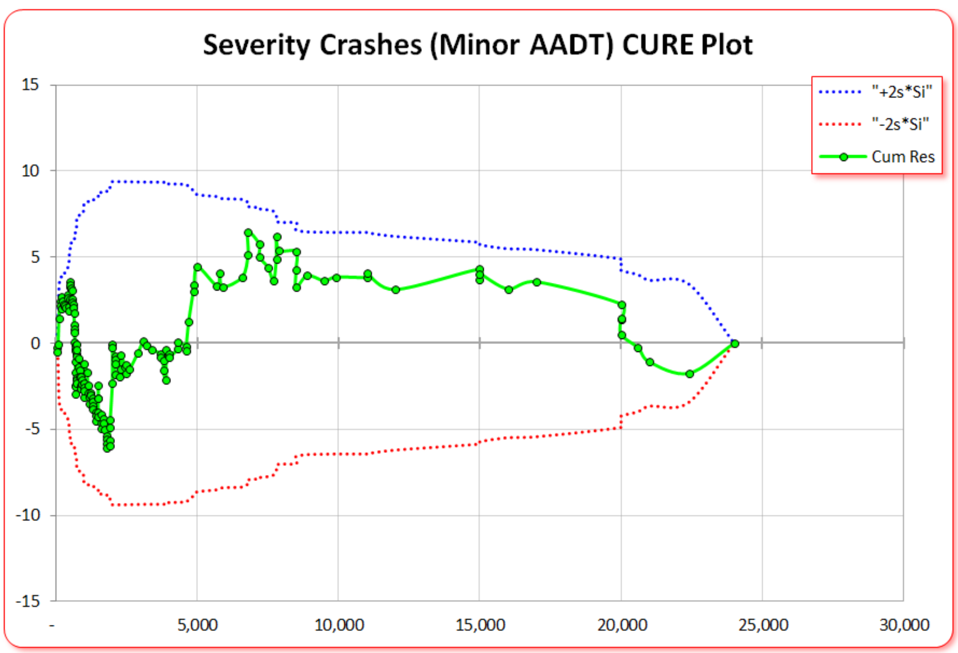

Figure 38. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	1.0000E-03
β_2	-2.0344E-01
β_3	1.1935E-01
β_4	7.0870E-01
α	7.1964E-01

Severity	
Variable	**Value**
β_1	1.0000E-03
β_2	-3.5777E-01
β_3	1.2395E-01
β_4	7.8878E-01
α	8.4841E-01

Figure 39. SPF Model Parameters, Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Rear End Collisions

Urban 4-Lane Divided Unsignalized 3-Leg Intersections, Broadside Crashes

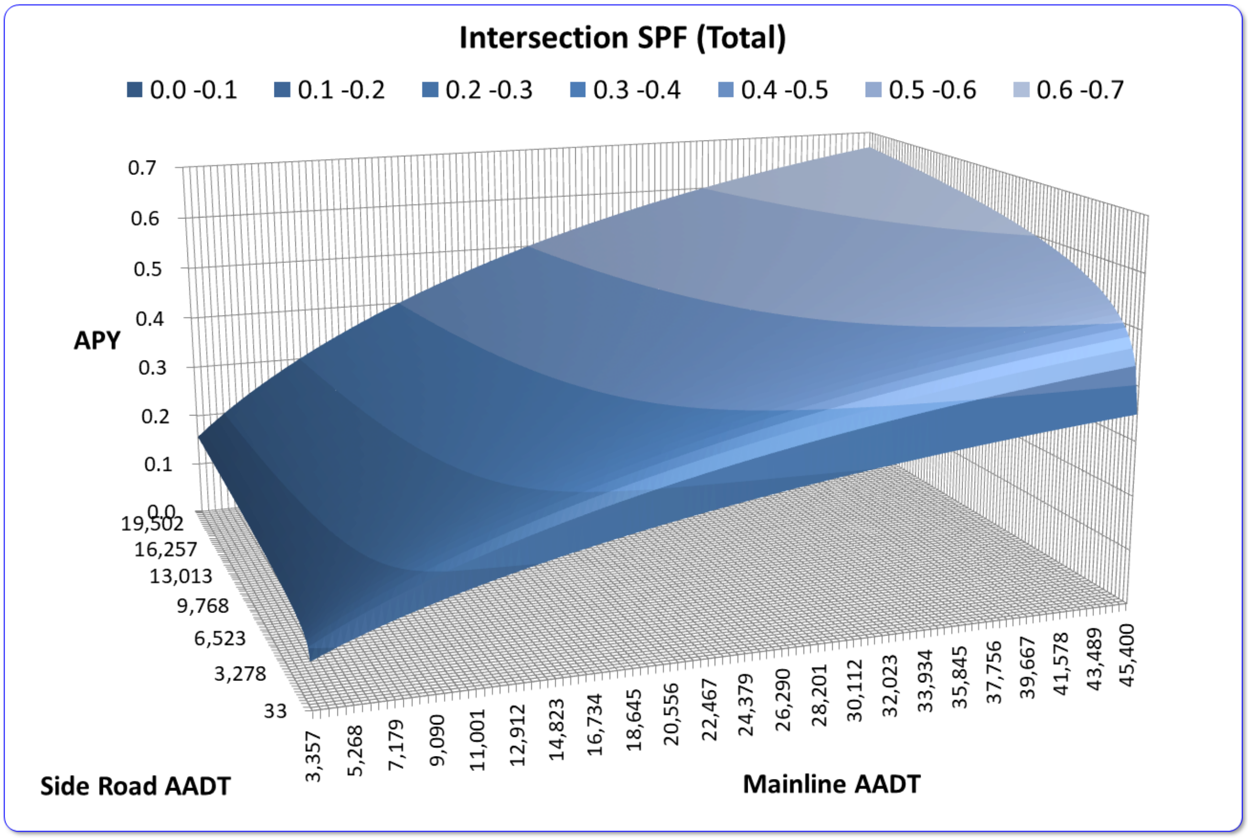

Figure 40. SPF – Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Total Model

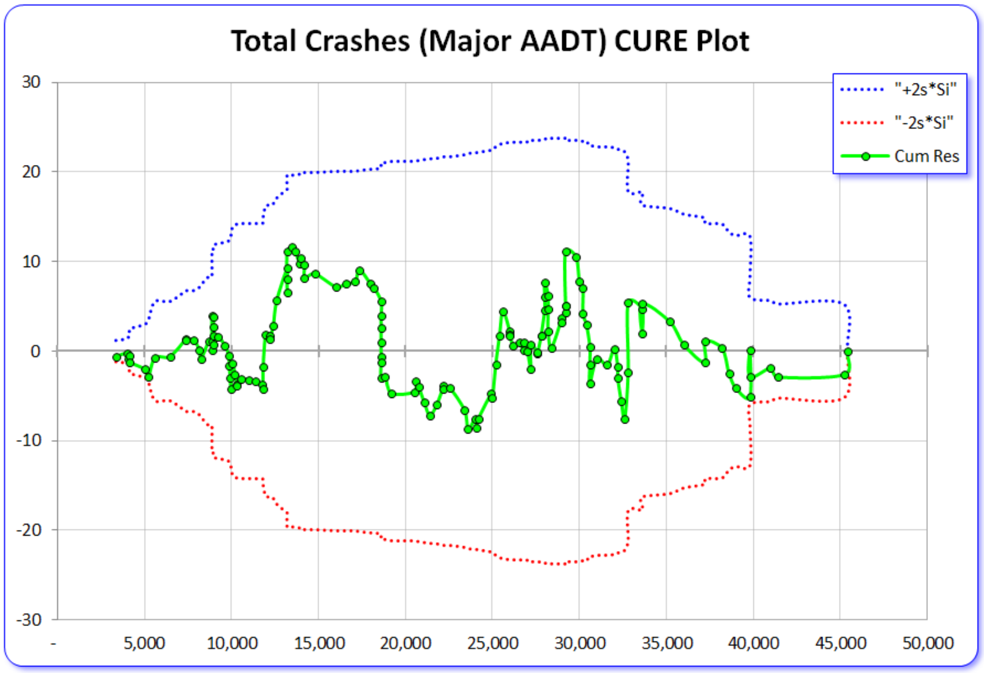

Figure 41. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Total Model

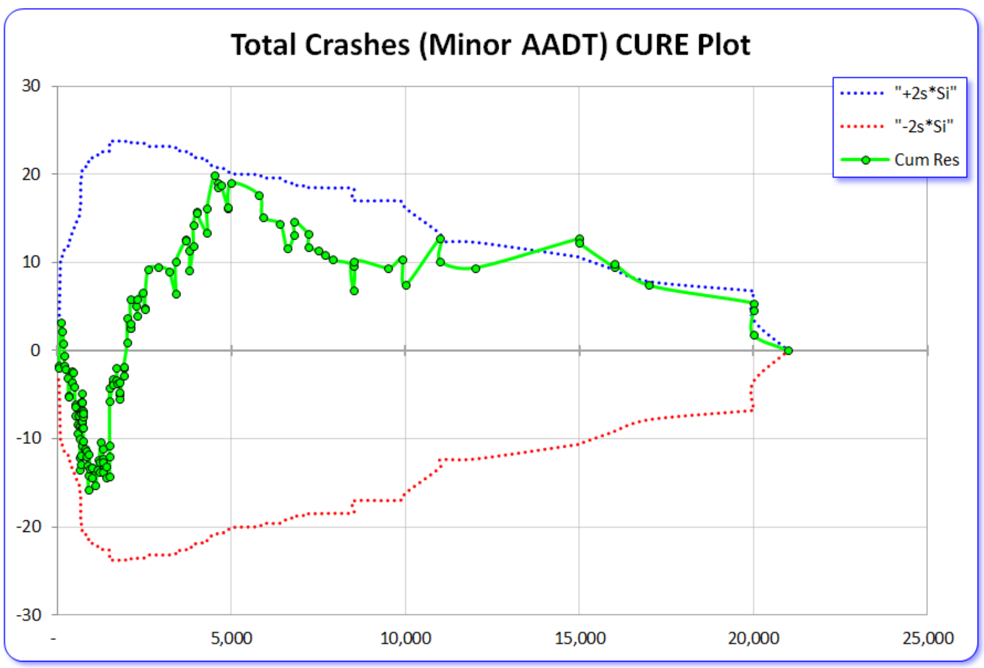

Figure 42. Figure 46 CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Total Model

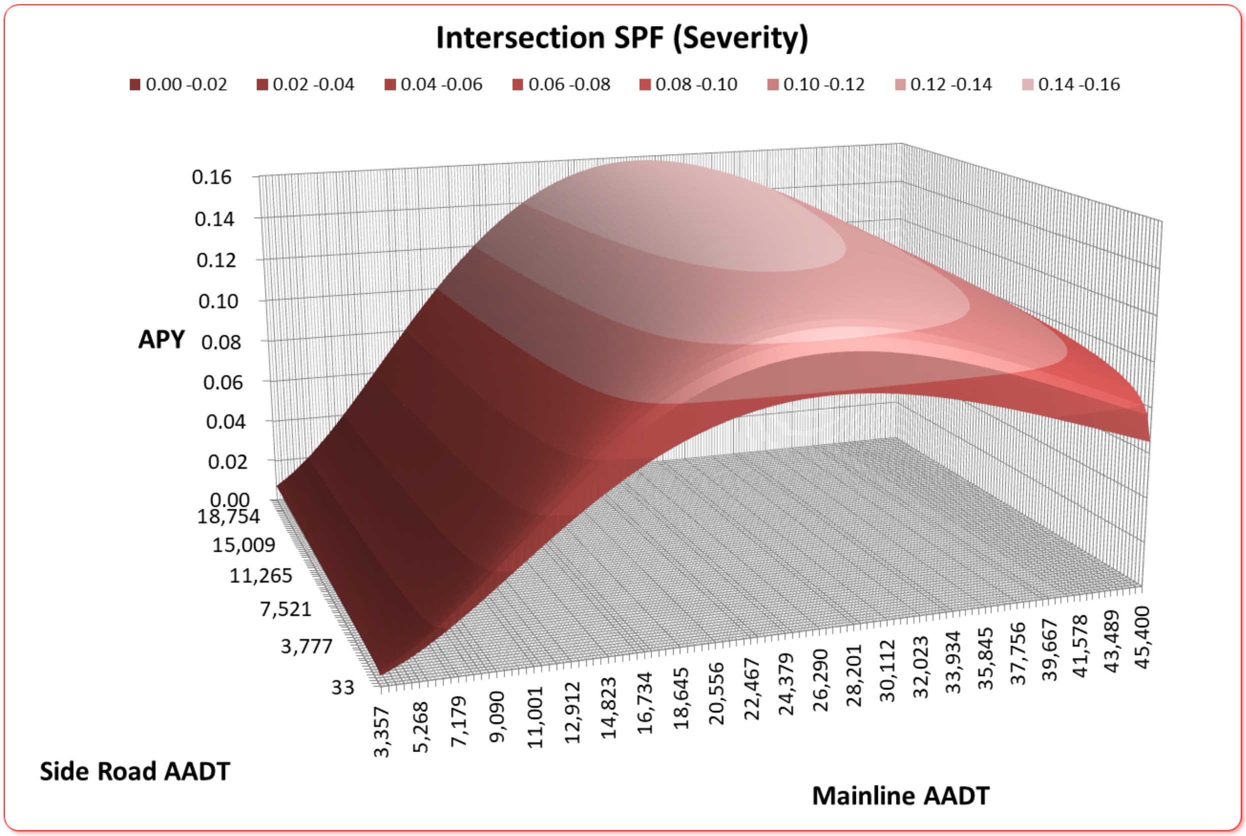

Figure 43. SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Severity Model

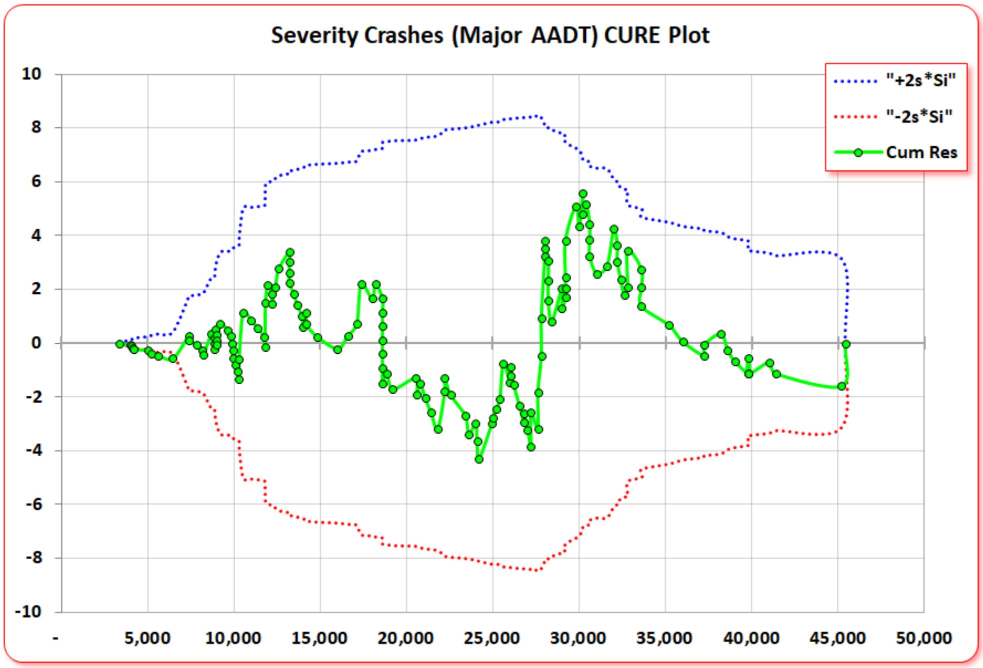

Figure 44. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Severity Model

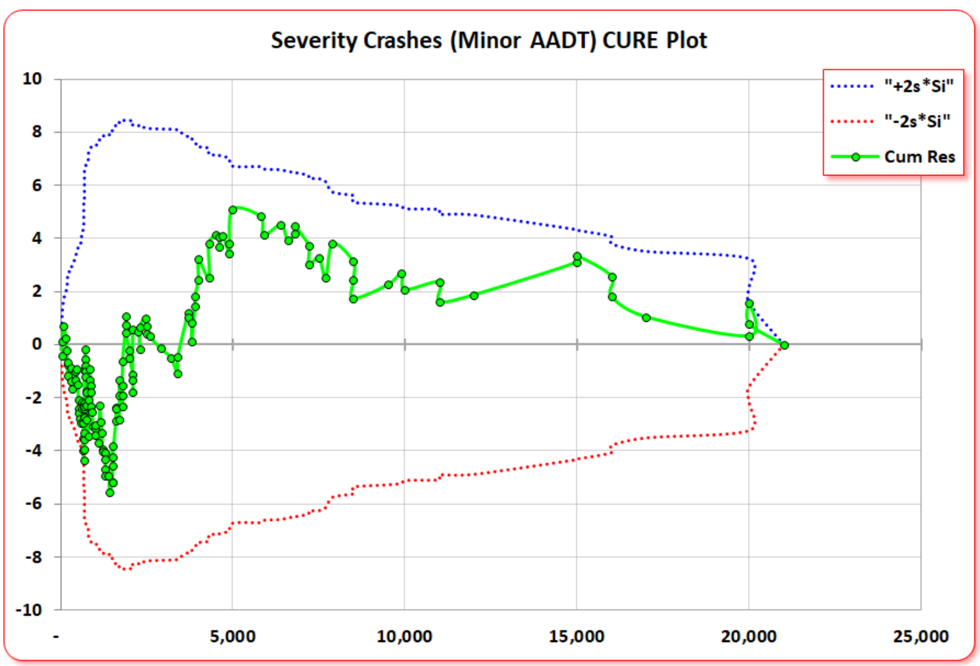

Figure 45. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency		Severity	
Variable	Value	Variable	Value
β_1	-6.7131E+00	β_1	-24417E+01
β_2	6.7619E-01	β_2	2.5486E-00
β_3	1.0053E-01	β_3	7.3316E-02
β_4	-7.3239E-02	β_4	-9.4580E-01
α	6.9839E-01	α	1.1628E-01

Figure 46. SPF Model Parameters, Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Broadside Crashes

Urban 4-Lane Divided Unsignalized 3-Leg Intersections, Approach Turn Crashes

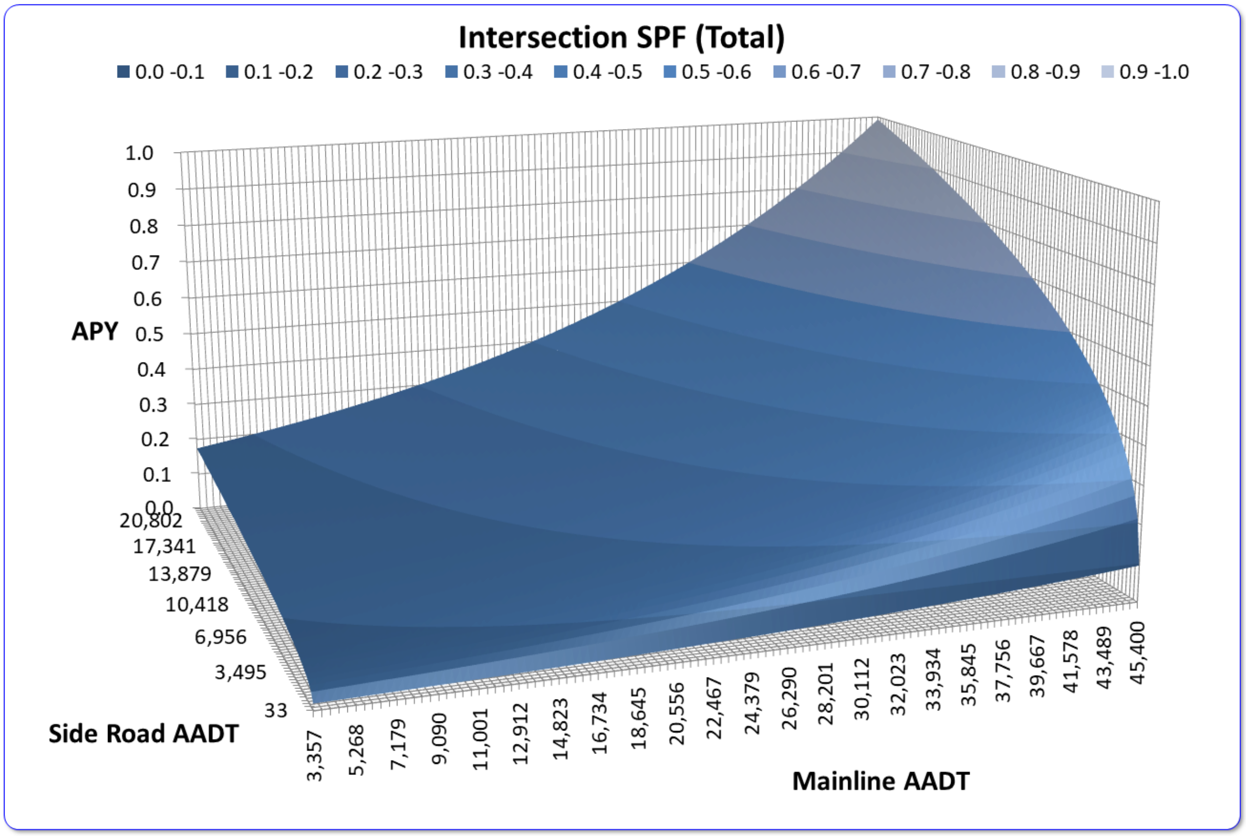

Figure 47. SPF – Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Total Model

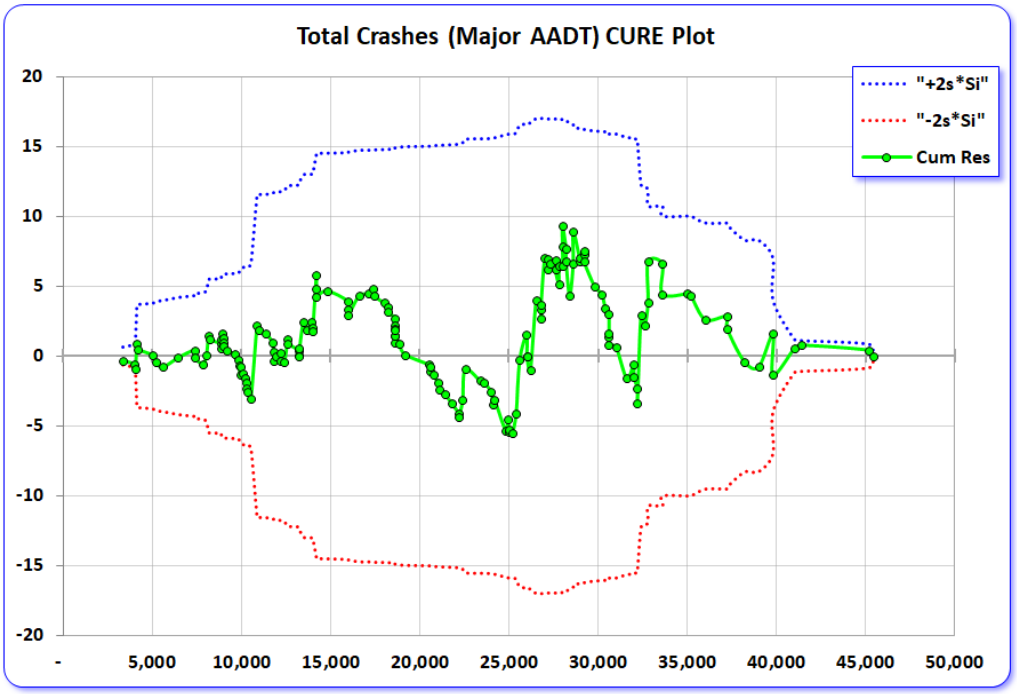

Figure 48. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Total Model

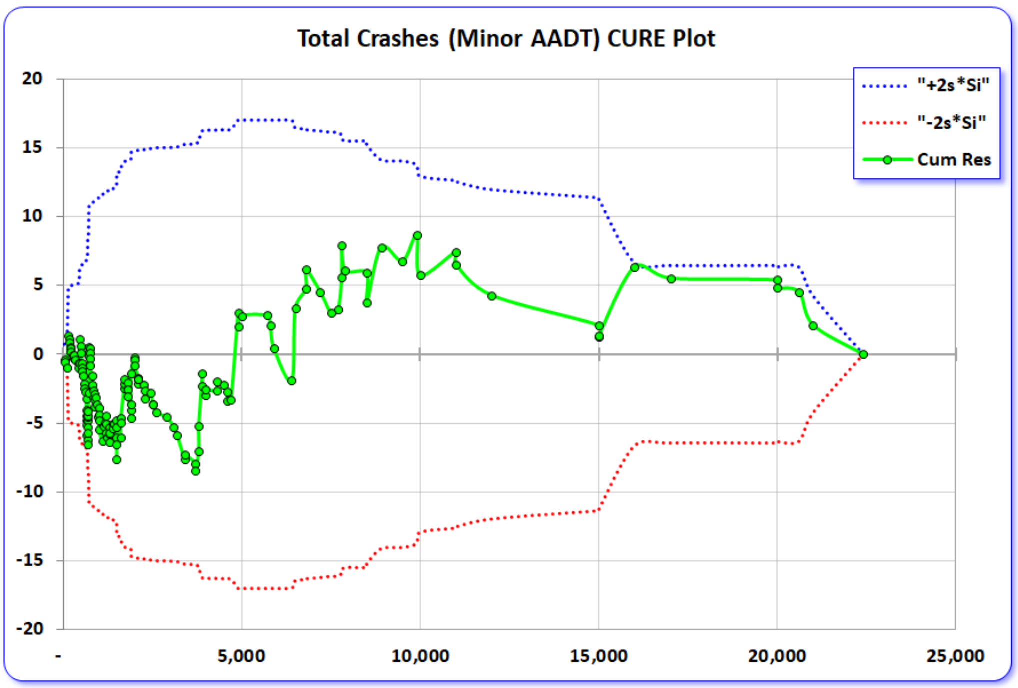

Figure 49. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Total Model

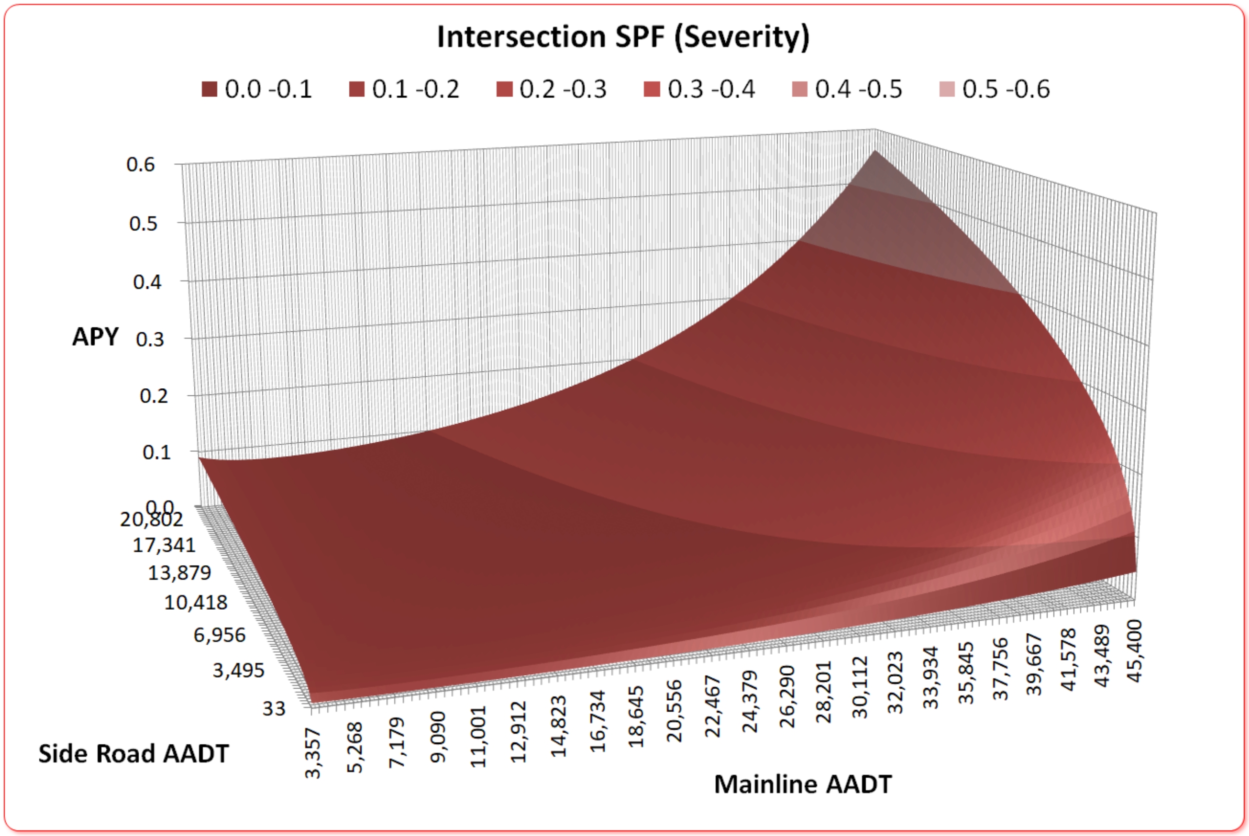

Figure 50. SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Severity Model

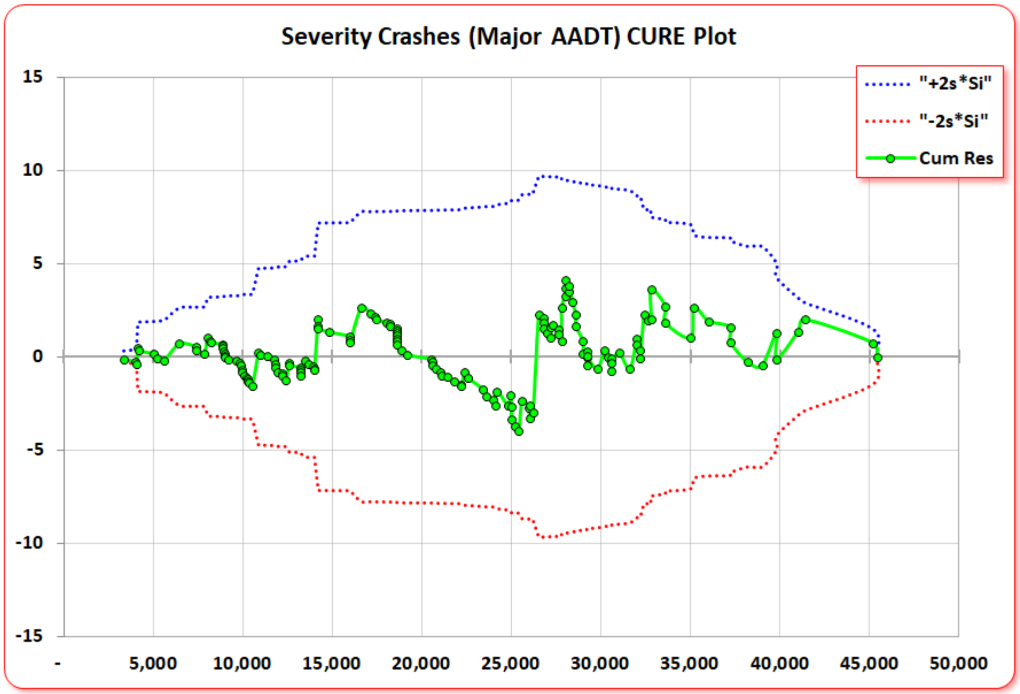

Figure 51. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Severity Model

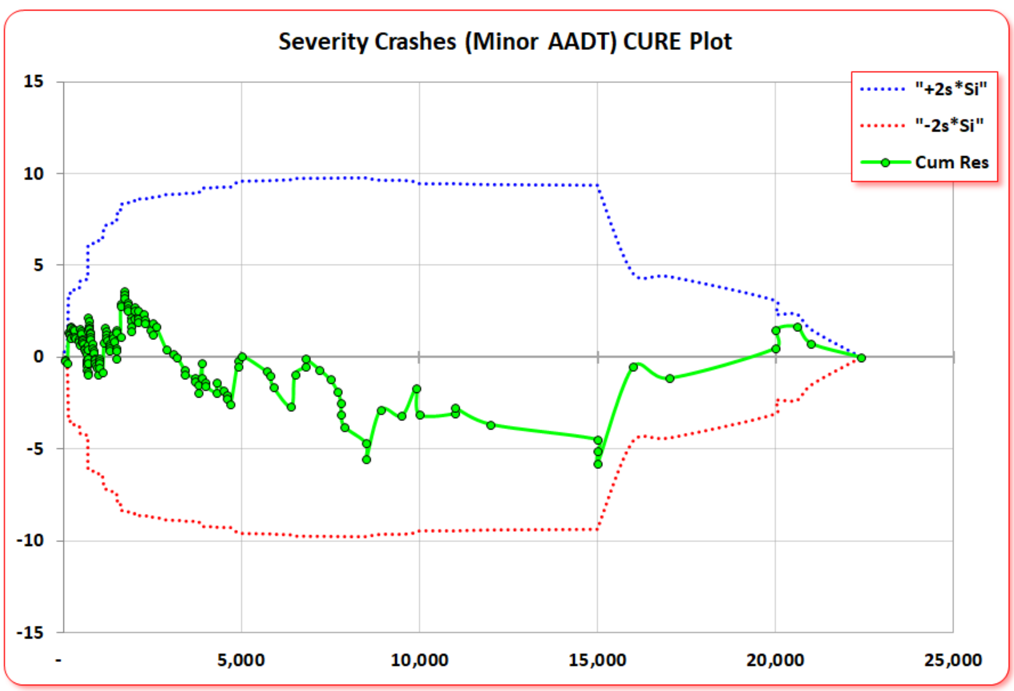

Figure 52. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	-3.9667E+00
β_2	1.0638E-02
β_3	3.6000E-01
β_4	4.0710E-01
α	8.6194E-01

Severity	
Variable	**Value**
β_1	1.8199E-01
β_2	-6.2859E-01
β_3	3.8471E-01
β_4	8.2324E-01
α	9.0909E-01

Figure 53. SPF Model Parameters, Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Approach Turn Crashes

Urban 4-Lane Divided Unsignalized 3-Leg Intersections, Same Direction Sideswipes

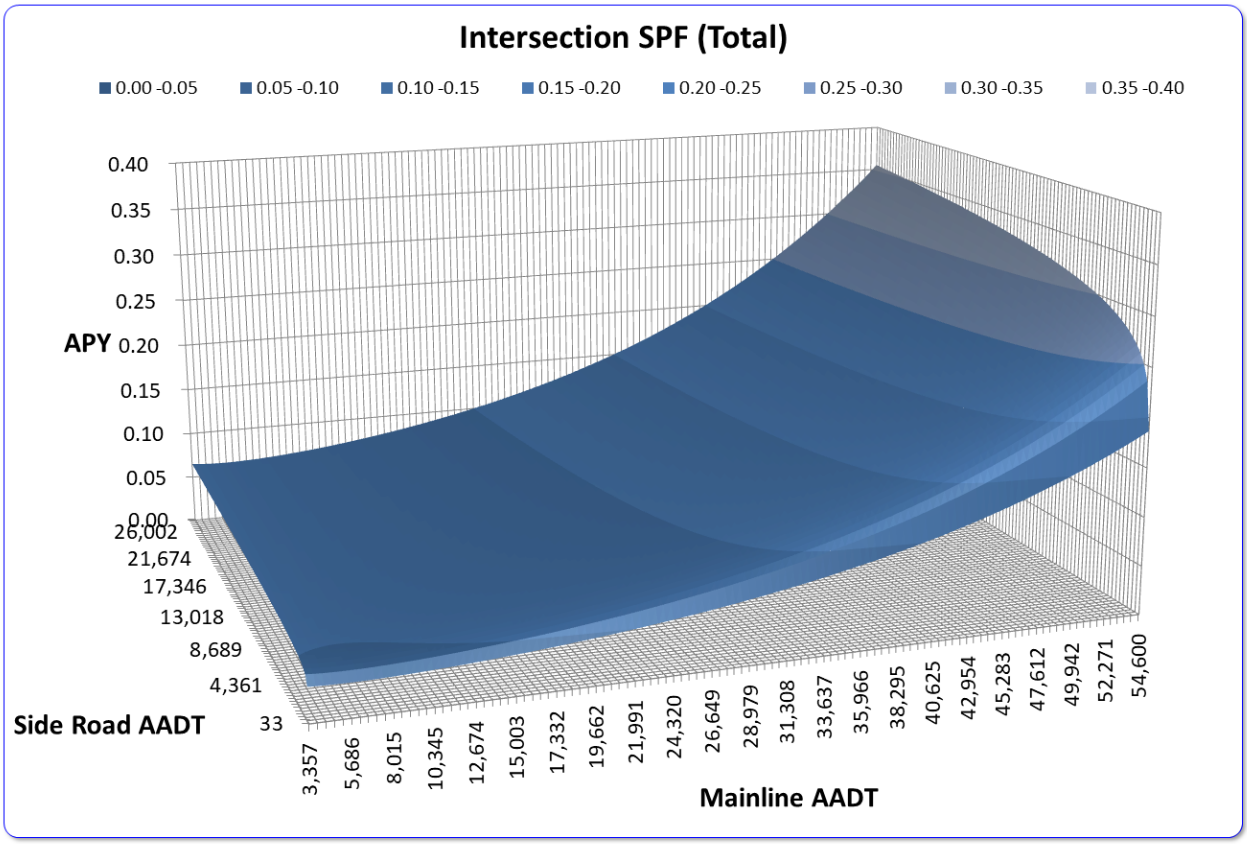

Figure 54. SPF – Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Total Model

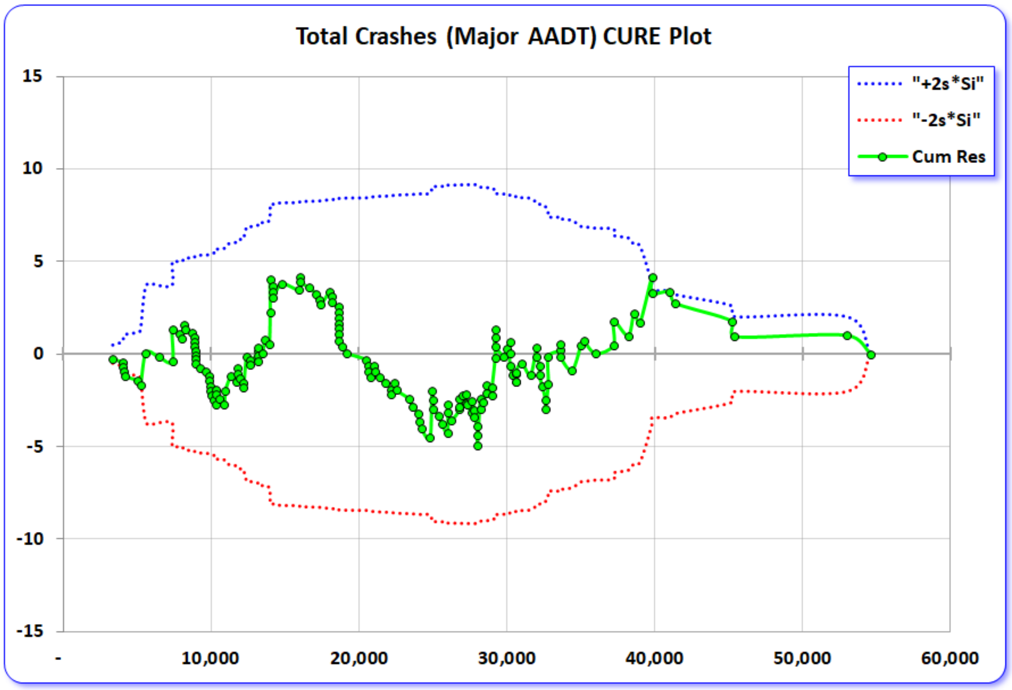

Figure 55. CURE Plot (Major AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Total Model

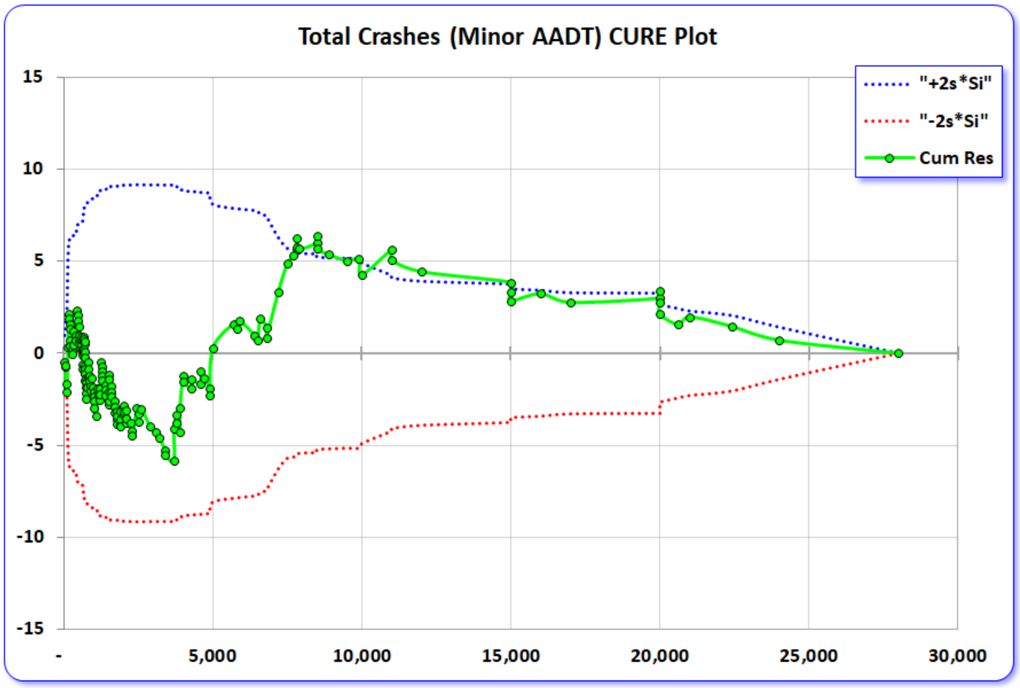

Figure 56. Figure 60 CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Total Model

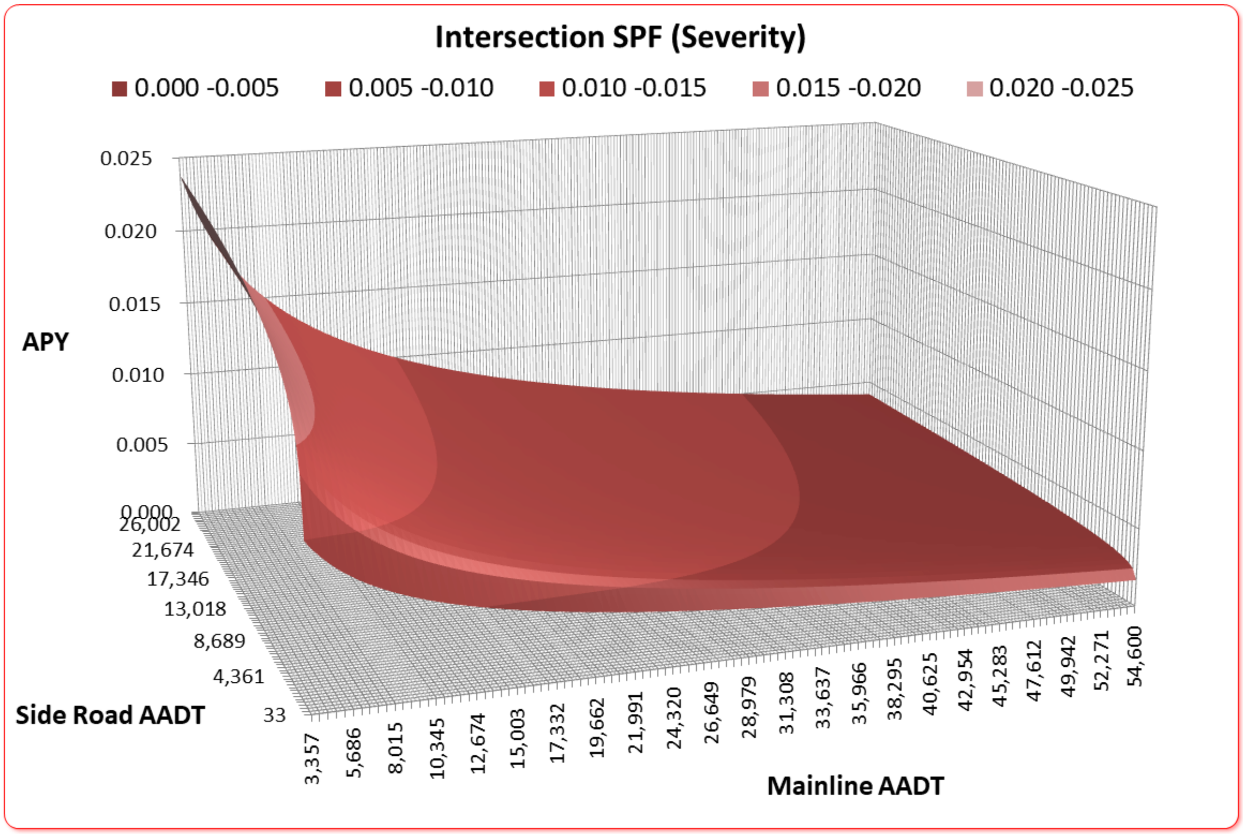

Figure 57. SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Severity Model

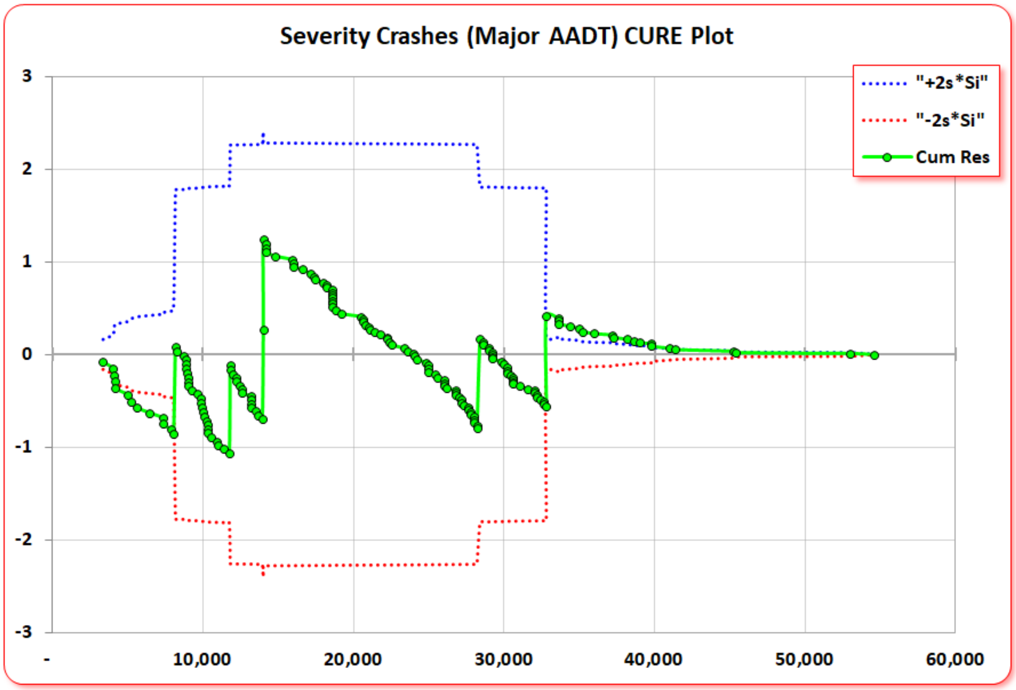

Figure 58. CURE (Major AADT) Plot SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Severity Model

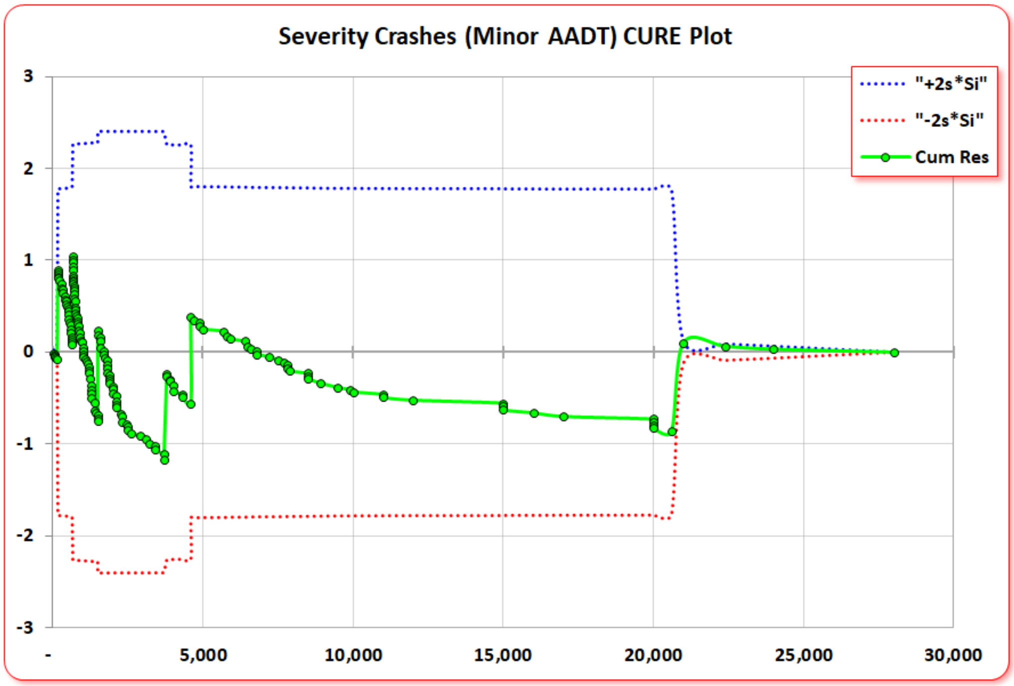

Figure 59. CURE Plot (Minor AADT) SPF - Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes – Severity Model

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10{,}000}\beta_4})$$

Frequency	
Variable	**Value**
β_1	1.0010E-03
β_2	-2.7798E-01
β_3	9.5180E-02
β_4	4.8170E-01
α	5.3459E-01

Severity	
Variable	**Value**
β_1	1.0000E-03
β_2	-4.2069E-01
β_3	1.2929E-01
β_4	-1.1692E-01
α	6.2172E-02

Figure 60. SPF Model Parameters, Urban 4-Lane Divided Unsignalized 3-Leg Intersections – Same Direction Sideswipes

Rural Flat and Rolling 2-Lane Highways, Fixed Object Collisions

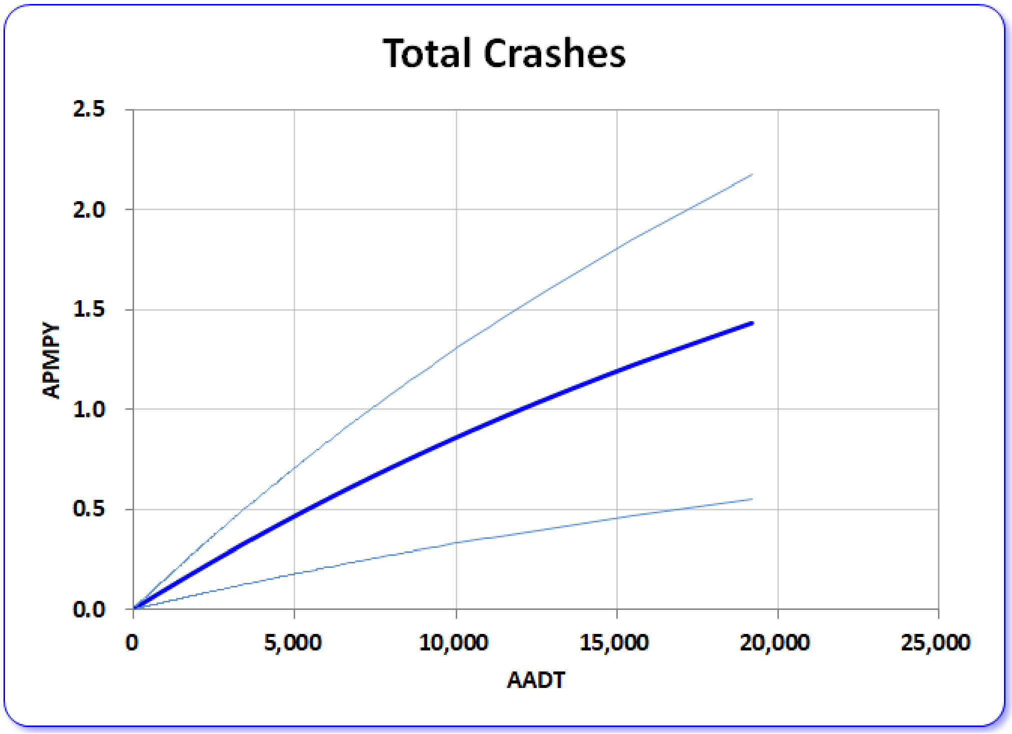

Figure 61. SPF - Rural Flat and Rolling 2-Lane Highways – Fixed Object Collisions – Total Model

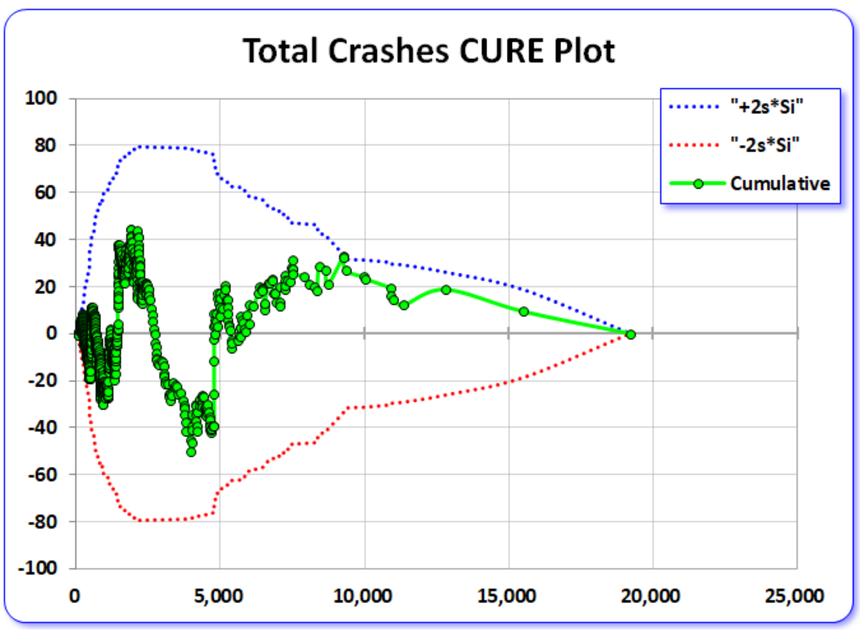

Figure 62. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Fixed Object Collisions–Total Model

Figure 63. SPF - Rural Flat and Rolling 2-Lane Highways – Fixed Object Collisions – Severity Model

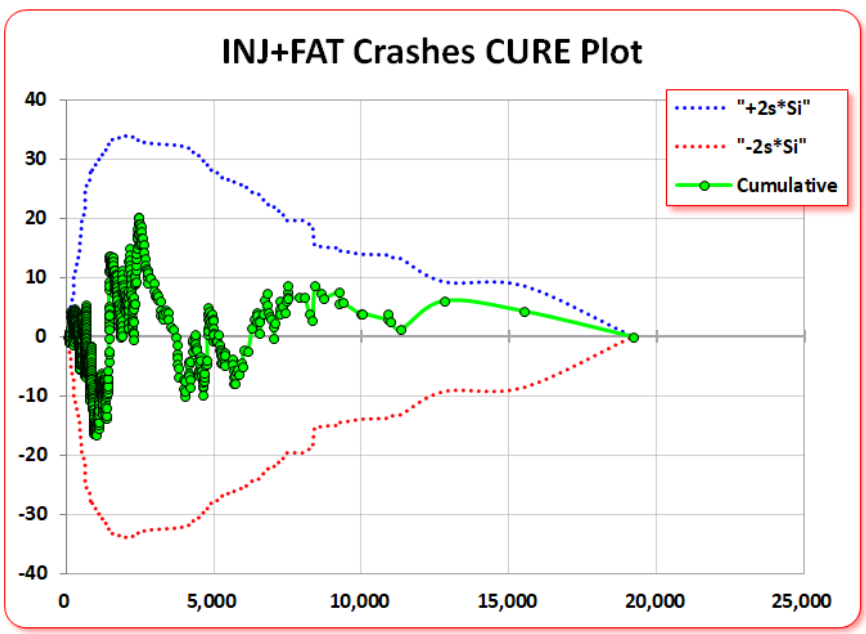

Figure 64. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Fixed Object Collisions-Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{\left(AADT^{\beta_2}\right) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency		Severity	
Variable	Value	Variable	Value
β_1	2.4867E+01	β_1	6.5371E+00
β_2	1.0171E+00	β_2	9.5516E-01
β_3	4.7000E+04	β_3	4.7000E+04
β_4	3.2145E-02	β_4	1.3626E-02
α	5.5554E-01	α	4.9358E-01

Figure 65. SPF Model Parameters, Rural Flat and Rolling 2-Lane Highways – Fixed Object Collisions

Rural Flat and Rolling 2-Lane Highways, Overturns

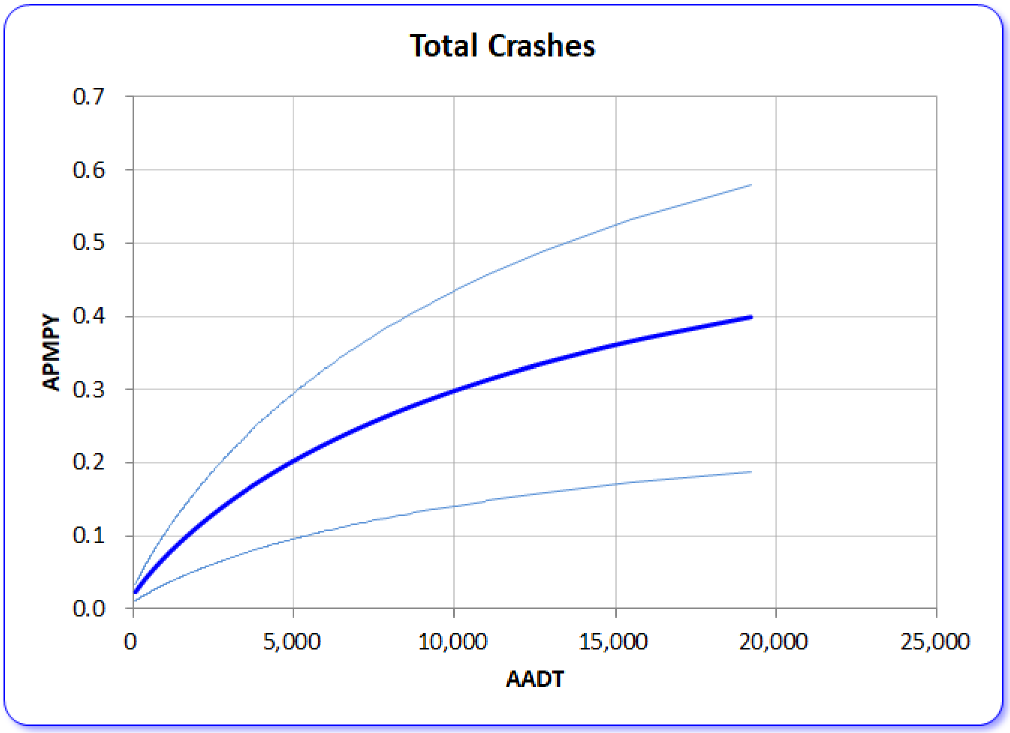

Figure 66. SPF - Rural Flat and Rolling 2-Lane Highways – Overturns– Total Model

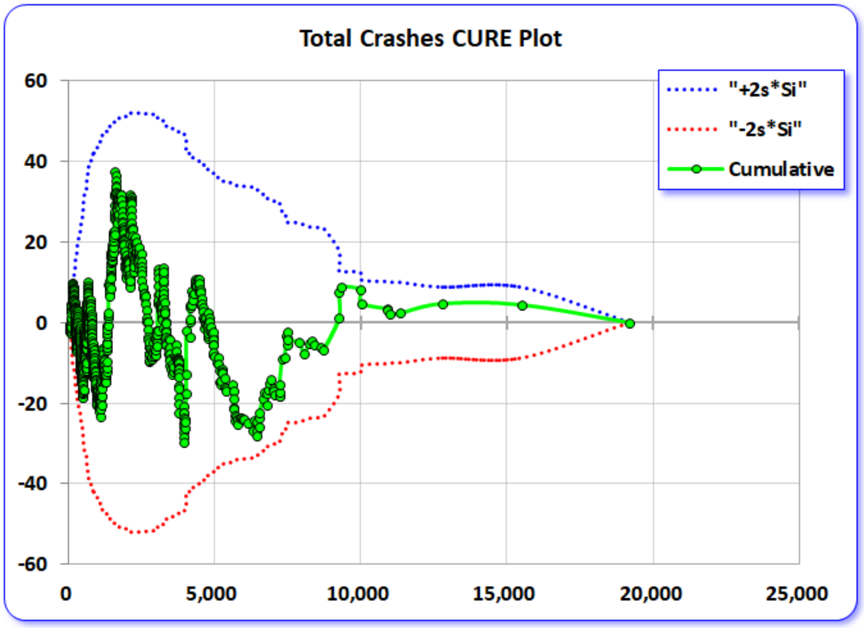

Figure 67. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Overturns– Total Model

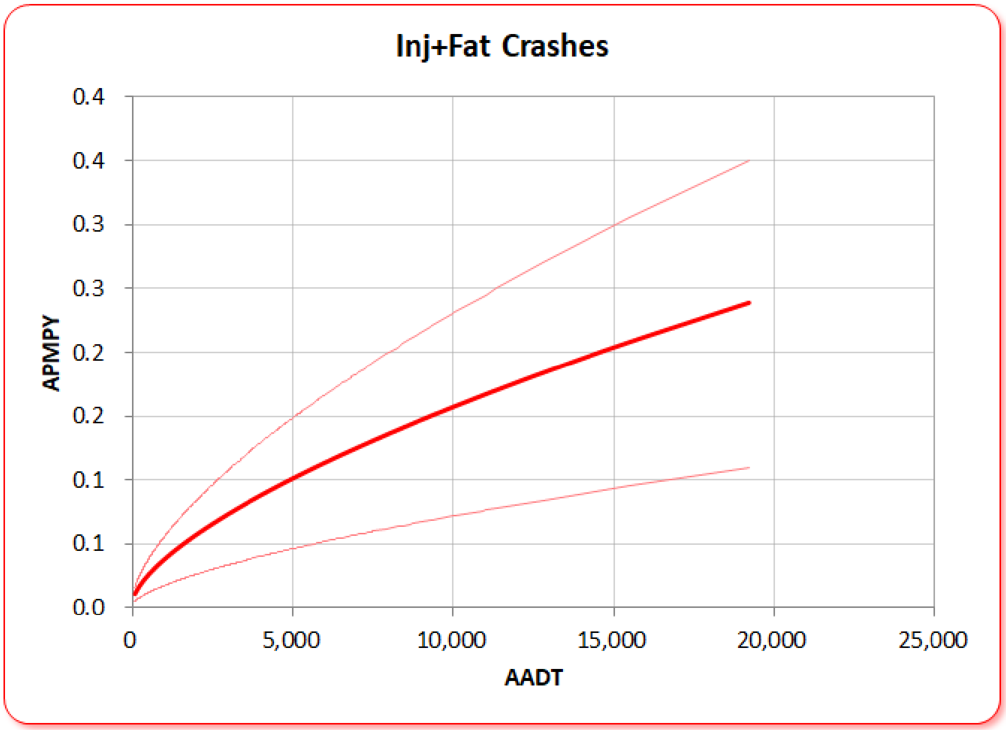

Figure 68. SPF - Rural Flat and Rolling 2-Lane Highways – Overturns– Severity Model

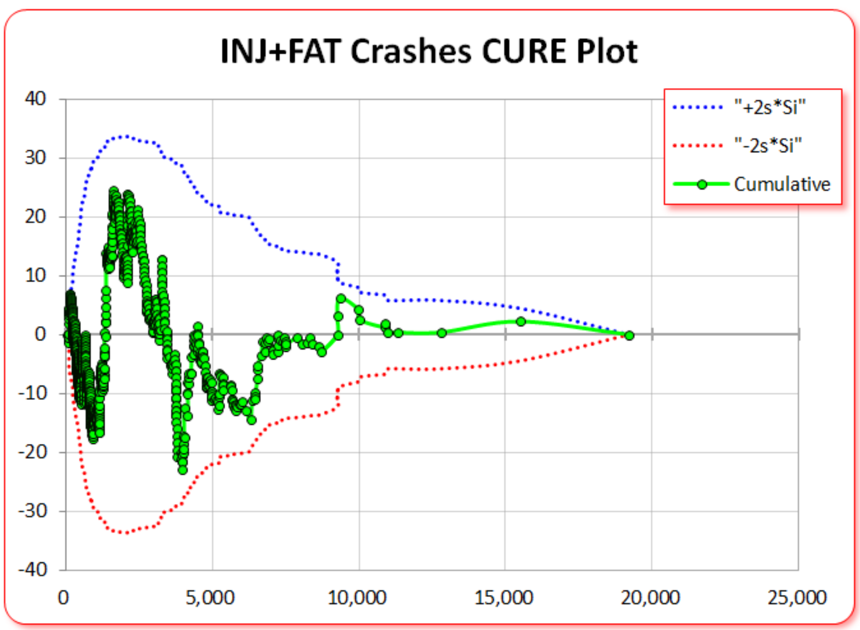

Figure 69. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Overturns– Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency	
Variable	Value
β_1	3.3705E+01
β_2	9.1845E-01
β_3	1.4487E+04
β_4	9.3015E-02
α	3.9353E-01

Severity	
Variable	Value
β_1	9.5858E+01
β_2	6.6655E-01
β_3	1.4046E+07
β_4	2.7578E-02
α	4.1920E-01

Figure 70. SPF Model Parameters, Rural Flat and Rolling 2-Lane Highways – Overturns

Rural Flat and Rolling 2-Lane Highways, Rear End Collisions

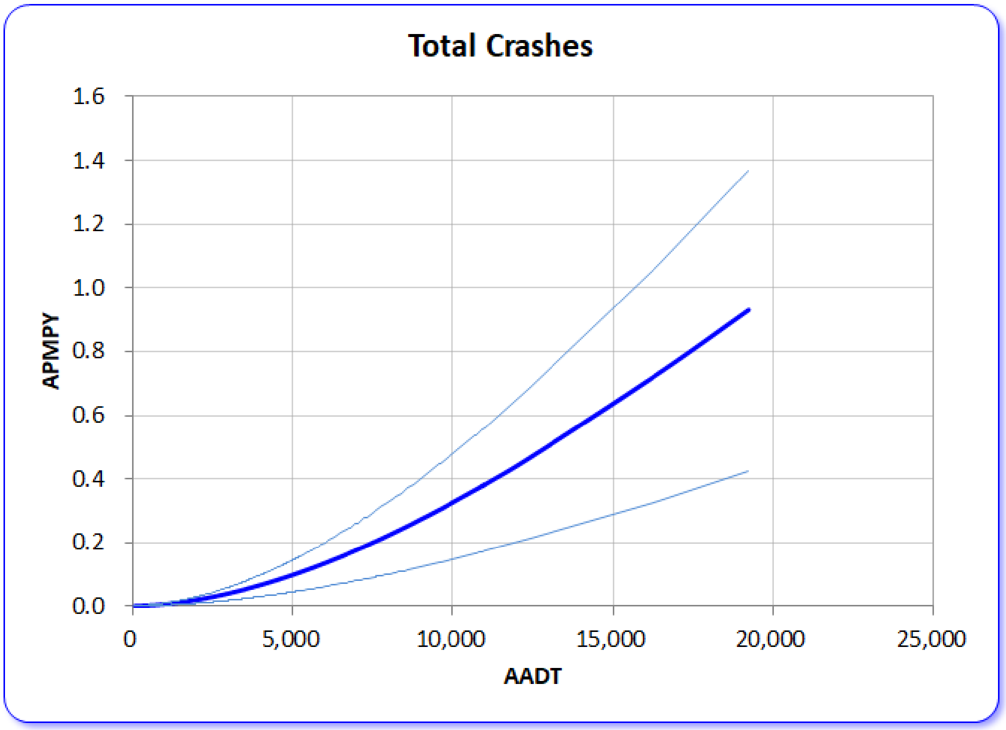

Figure 71. SPF - Rural Flat and Rolling 2-Lane Highways – Rear End Collisions – Total Model

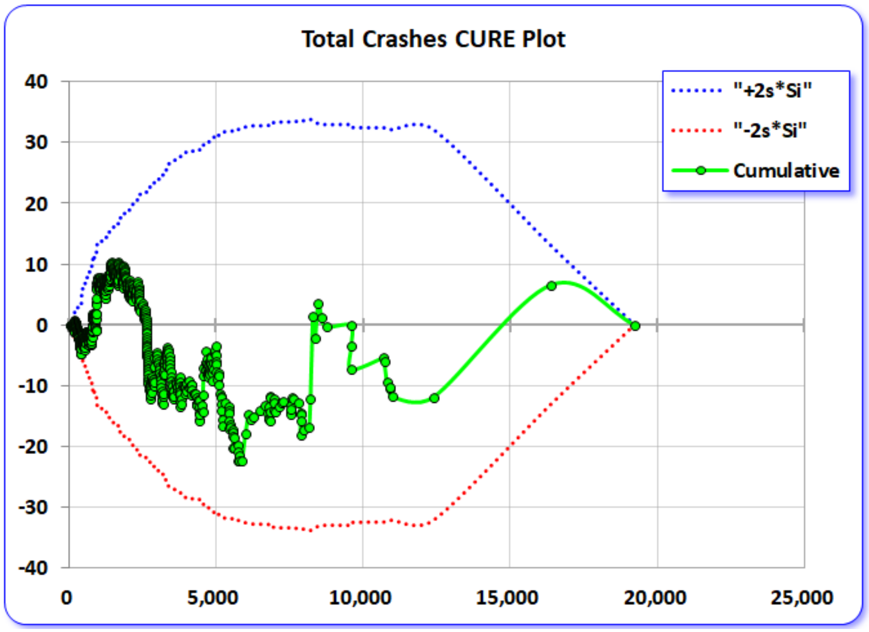

Figure 72. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Rear End Collisions – Total Model

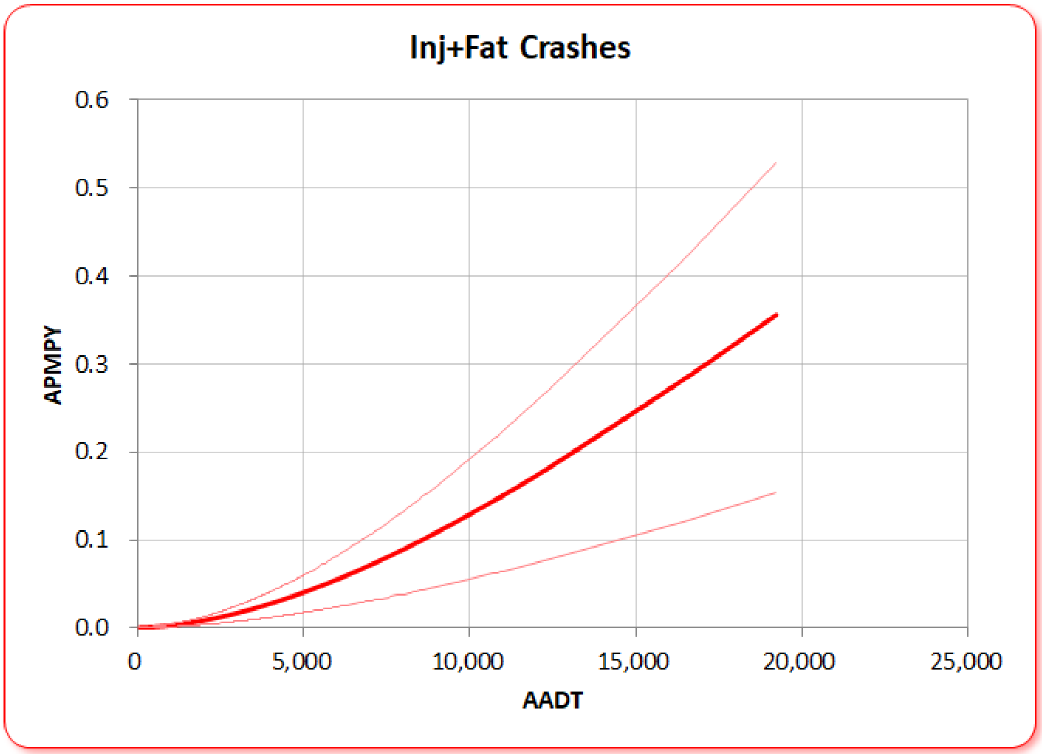

Figure 73. SPF - Rural Flat and Rolling 2-Lane Highways – Rear End Collisions – Severity Model

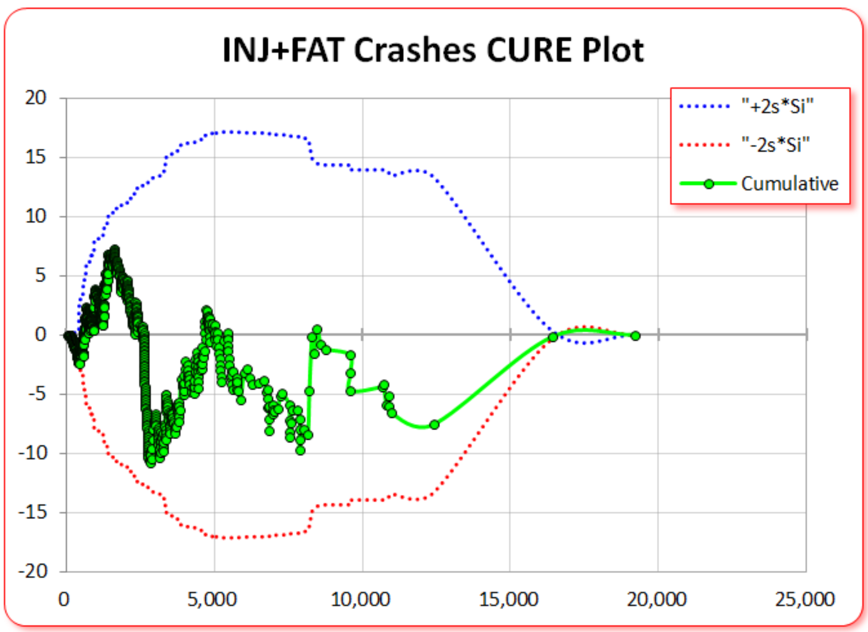

Figure 74. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Rear End Collisions – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency	
Variable	**Value**
β_1	2.7740E+01
β_2	1.7938E+00
β_3	4.7001E+04
β_4	6.6056E-03
α	4.2363E-01

Severity	
Variable	**Value**
β_1	1.025E+01
β_2	1.7464E+00
β_3	4.7001E+04
β_4	1.9605E-03
α	4.6600E-01

Figure 75. SPF Model Parameters, Rural Flat and Rolling 2-Lane Highways – Rear End Collisions

Rural Flat and Rolling 2-Lane Highways, Wild Animal Collisions

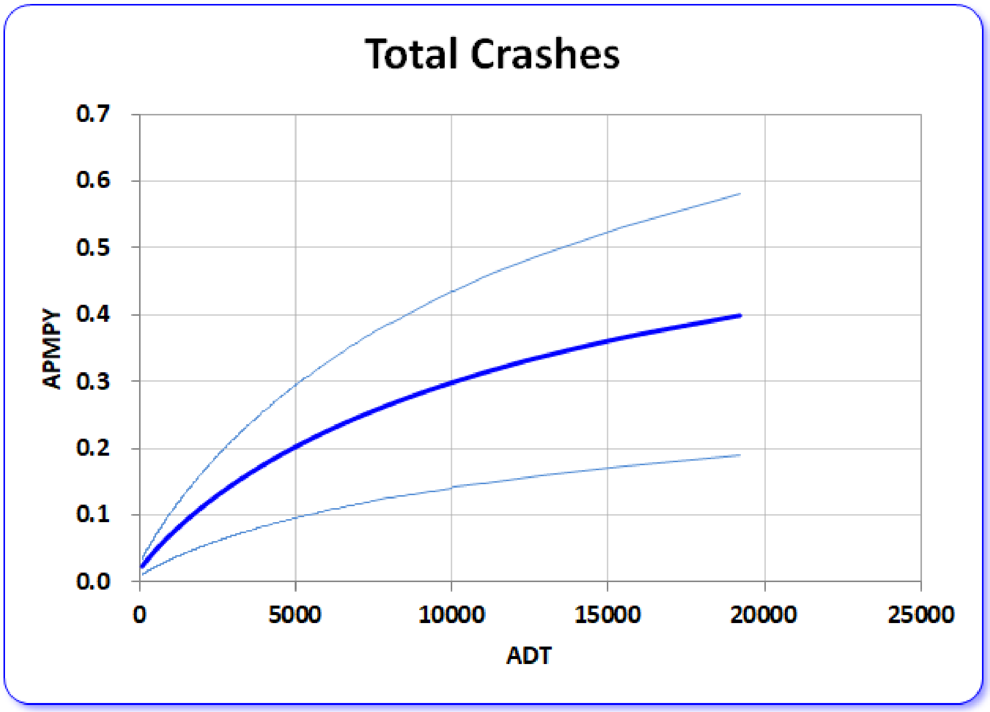

Figure 76. SPF - Rural Flat and Rolling 2-Lane Highways – Wild Animal Collisions – Total Model

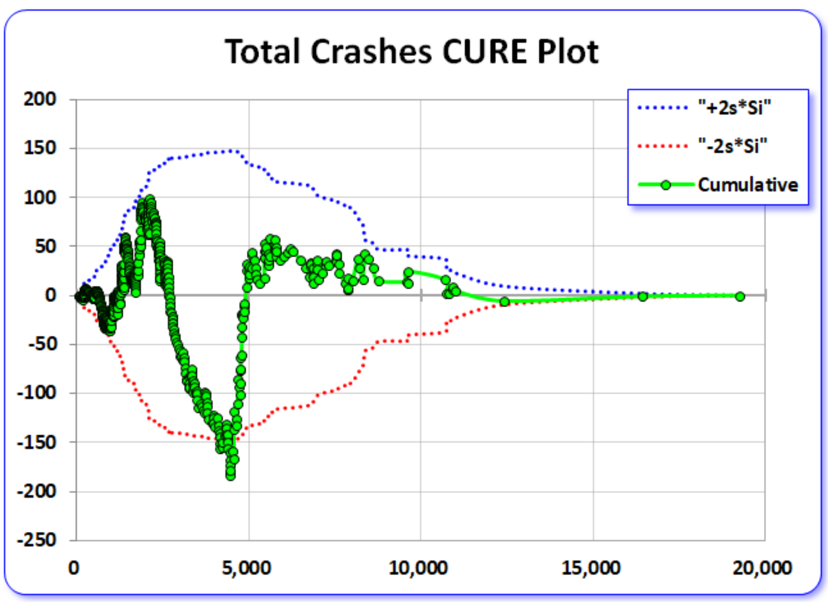

Figure 77. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Wild Animal Collisions – Total Model

Figure 78. SPF - Rural Flat and Rolling 2-Lane Highways – Wild Animal Collisions – Severity Model

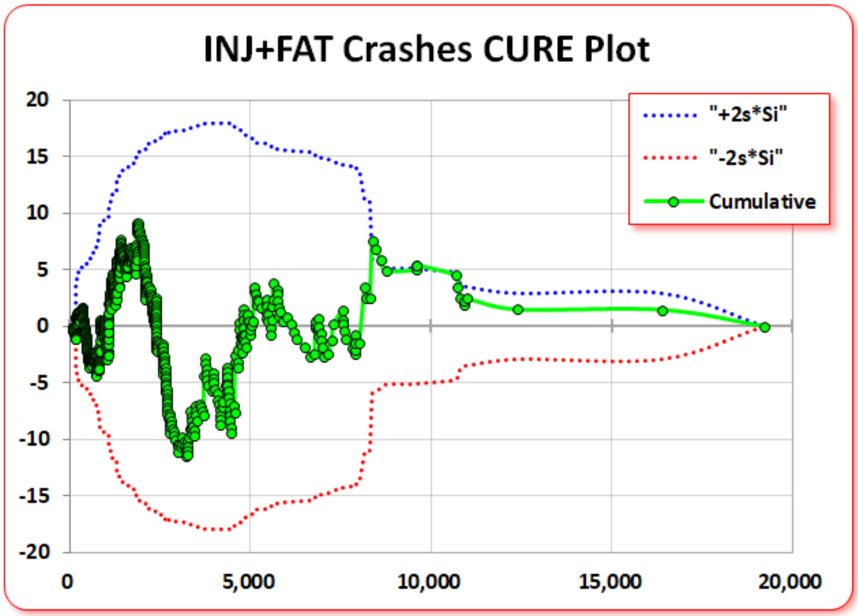

Figure 79. CURE Plot SPF - Rural Flat and Rolling 2-Lane Highways – Wild Animal Collisions – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency	
Variable	Value
β_1	8.0133E+00
β_2	1.4450E+00
β_3	6.7176E+03
β_4	9.0506E-02
α	1.4241E+00

Severity	
Variable	Value
β_1	6.9058E-01
β_2	1.4536E+00
β_3	8.8484E+03
β_4	1.7032E-02
α	1.2045E+00

Figure 80. SPF Model Parameters, Rural Flat and Rolling 2-Lane Highways – Wild Animal Collisions

Urban 4-Lane Freeways, Rear End Collisions

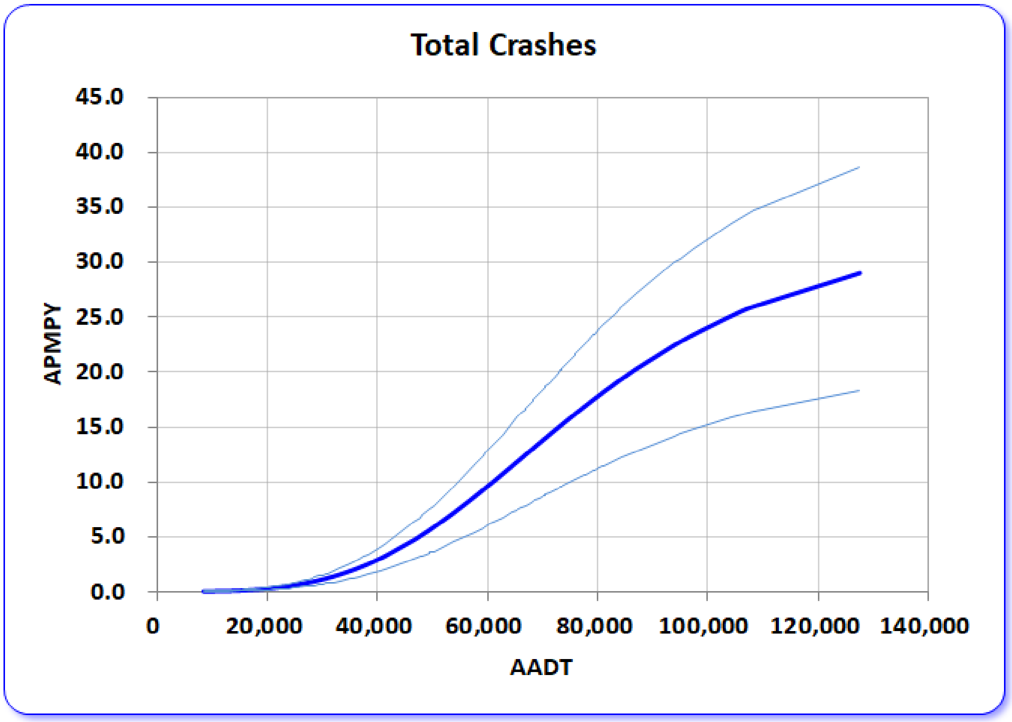

Figure 81. SPF – Urban 4-Lane Freeways – Rear End Collisions – Total Model

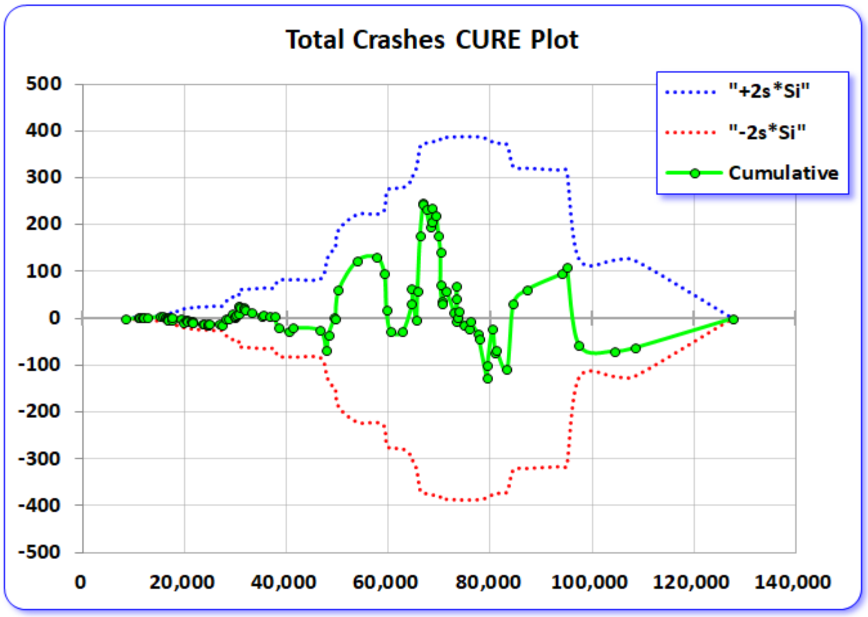

Figure 82. CURE Plot SPF - Urban 4-Lane Freeways – Rear End Collisions – Total Model

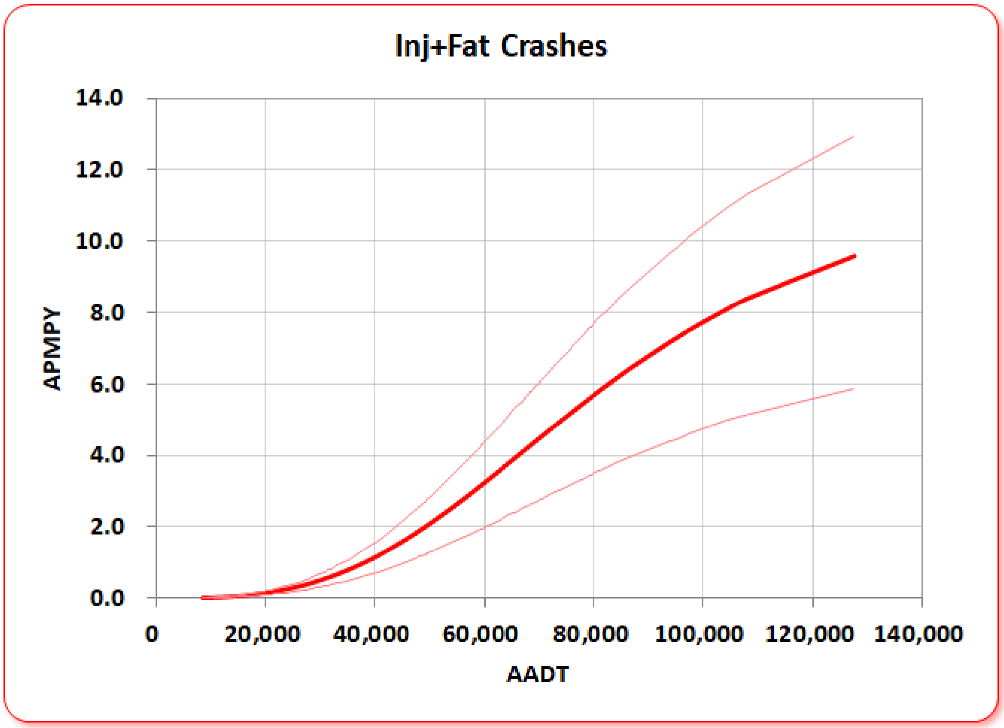

Figure 83. SPF - Urban 4-Lane Freeways – Rear End Collisions – Severity Model

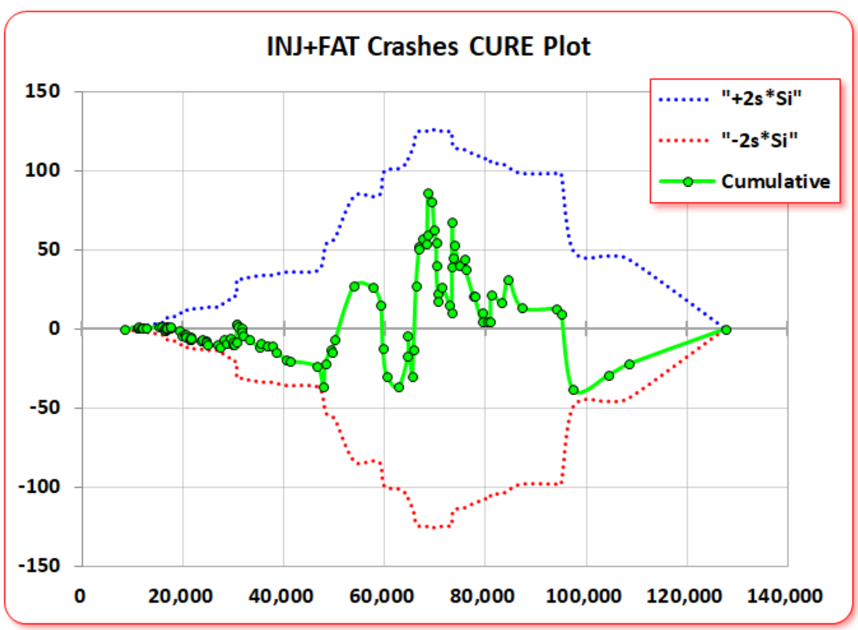

Figure 84. CURE Plot SPF - Urban 4-Lane Freeways – Rear End Collisions – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency		Severity	
Variable	Value	Variable	Value
β_1	1.6986E+02	β_1	6.1000E+01
β_2	3.5598E+00	β_2	3.0703E+00
β_3	7.8099E+04	β_3	8.3604E+04
β_4	3.6993E-01	β_4	1.0000E-03
α	1.8618E-01	α	2.0524E-01

Figure 85. SPF Model Parameters, Urban 4-Lane Freeways – Rear End Collisions

Urban Freeways, Sideswipe (Same Direction)

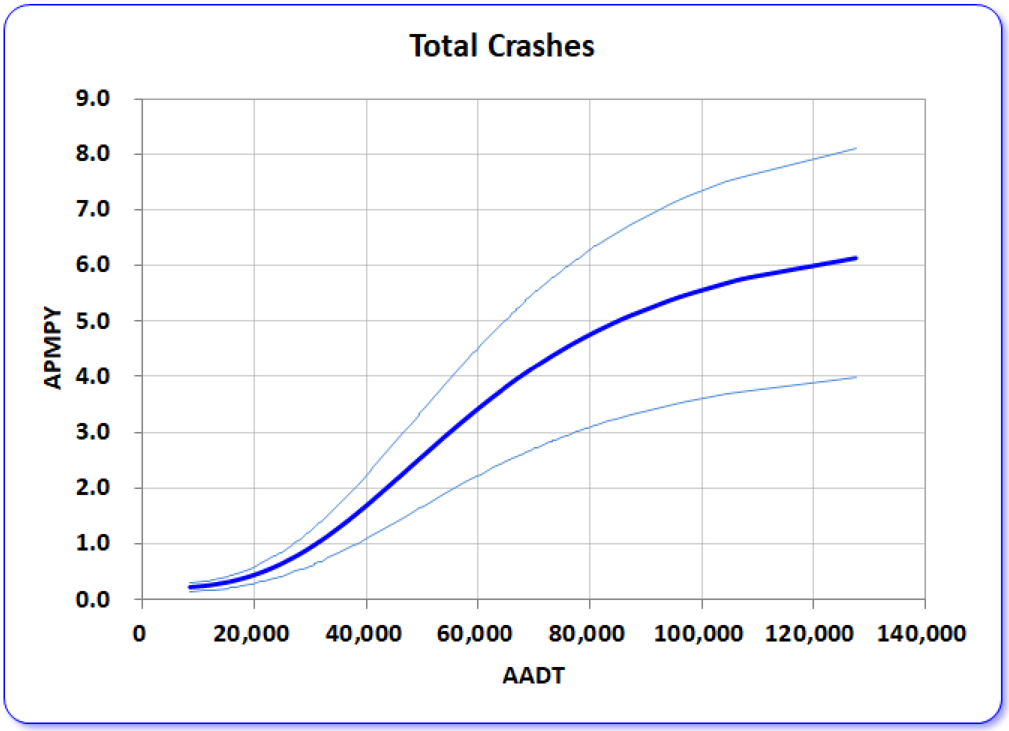

Figure 86. SPF – Urban 4-Lane Freeways – Sideswipe (Same Direction) – Total Model

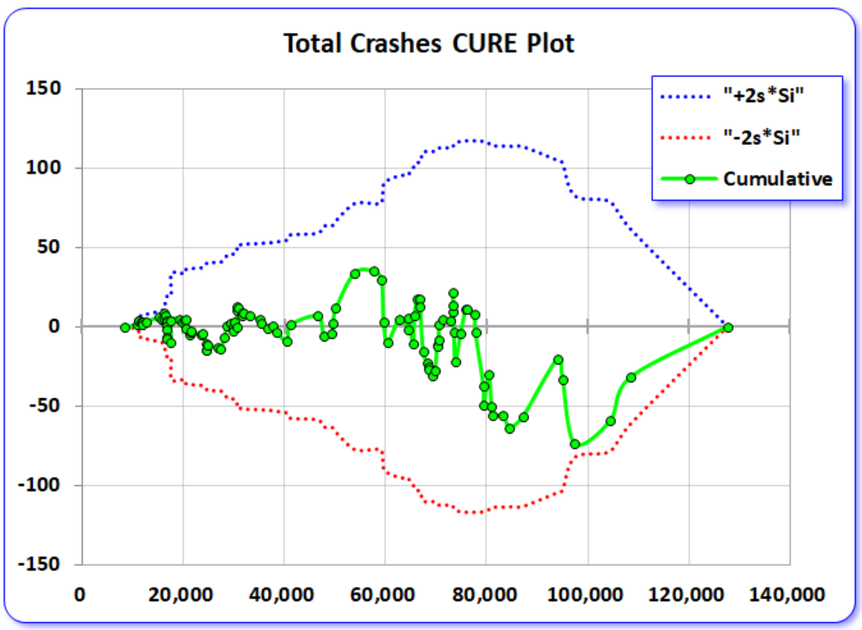

Figure 87. CURE Plot SPF - Urban Flat and Rolling 4-Lane Freeways – Sideswipe (Same Direction) – Total Model

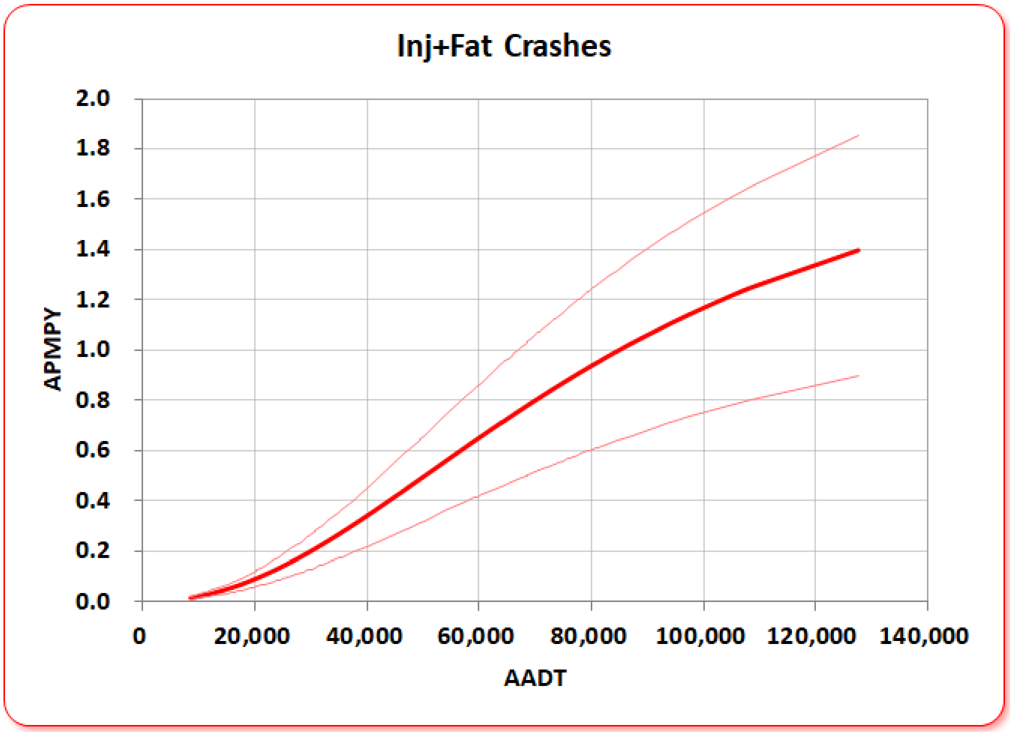

Figure 88. SPF - Urban 4-Lane Freeways – Sideswipe (Same Direction) – Severity Model

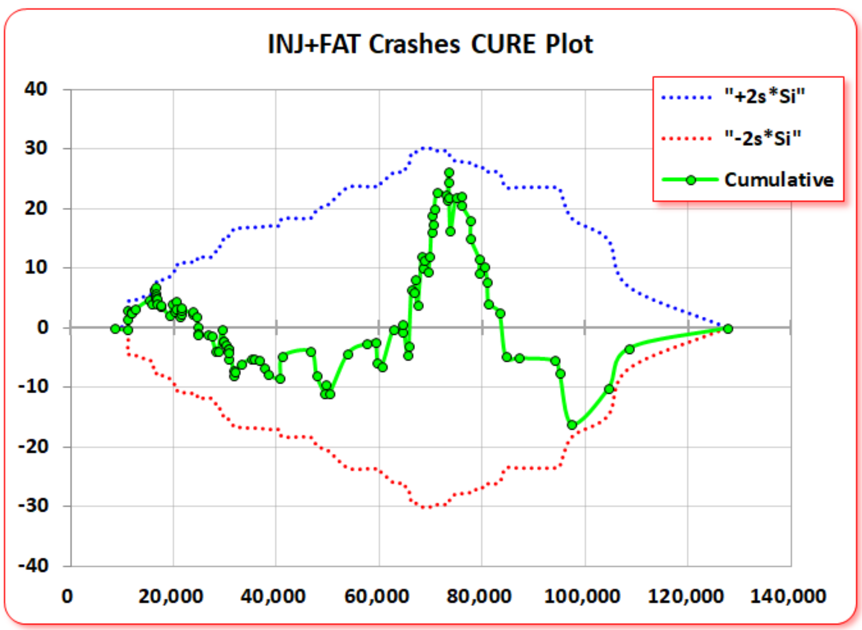

Figure 89. CURE Plot SPF - Urban 4-Lane Freeways – Sideswipe (Same Direction) – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency		Severity	
Variable	Value	Variable	Value
β_1	3.3012E+01	β_1	9.8394E+00
β_2	2.9419E+00	β_2	2.1220E+00
β_3	6.1002E+04	β_3	8.3604E+04
β_4	1.0396E+00	β_4	1.0000E-03
α	1.6804E-01	α	1.7393E-01

Figure 90. SPF Model Parameters, Urban 4-Lane Freeways – Sideswipe (Same Direction)

Urban 4-Lane Freeways, Fixed Object Collisions

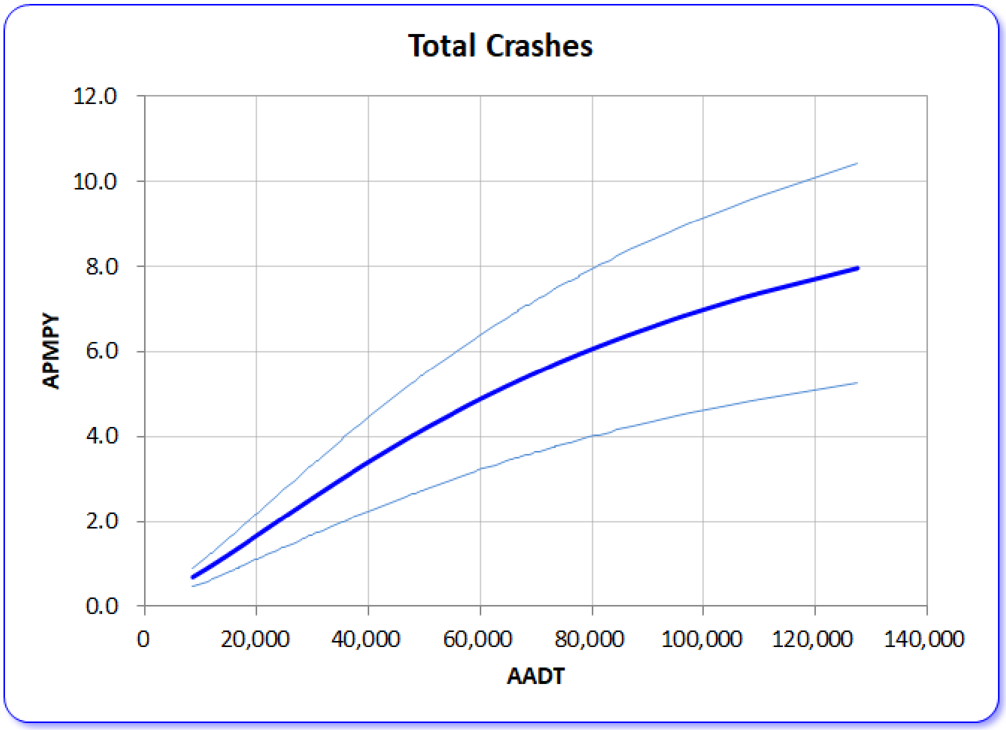

Figure 91. SPF – Urban 4-Lane Freeways – Fixed Object Collisions – Total Model

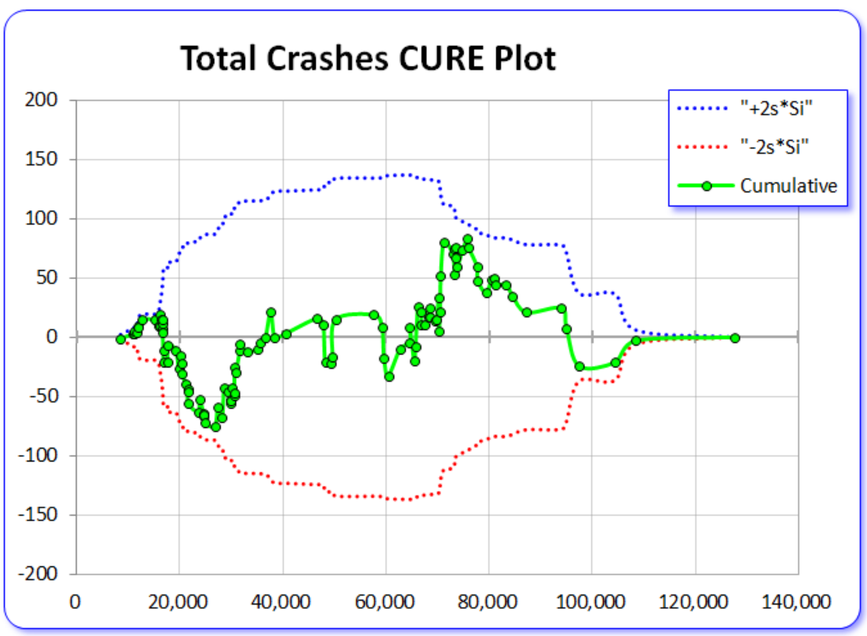

Figure 92. CURE Plot SPF - Urban 4-Lane Freeways – Fixed Object Collisions – Total Model

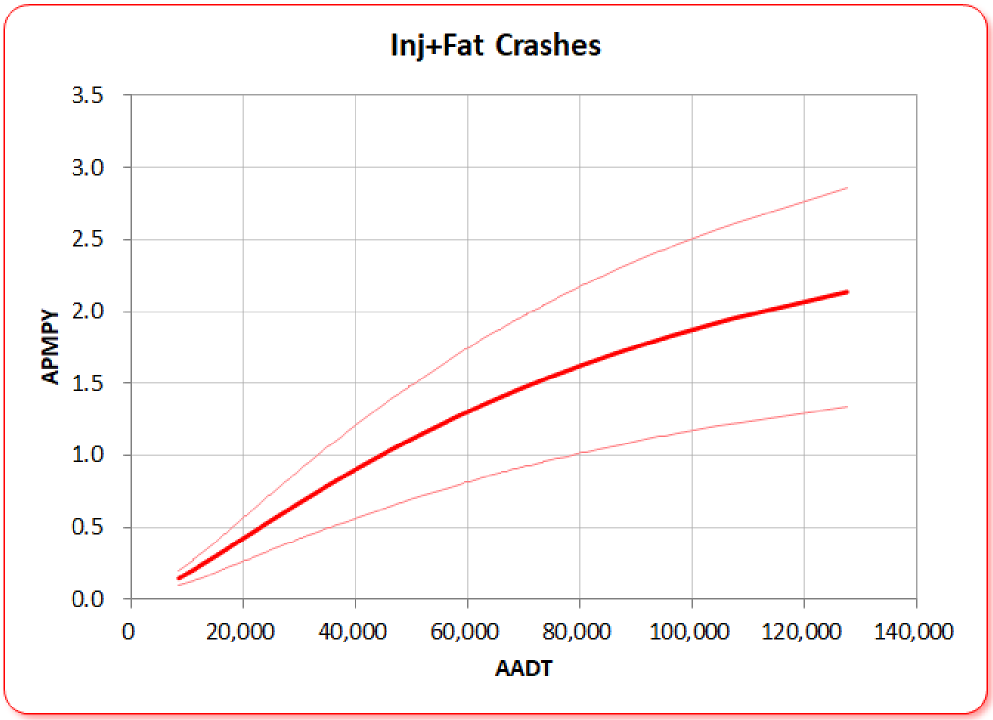

Figure 93. SPF - Urban 4-Lane Freeways – Fixed Object Collisions – Severity Model

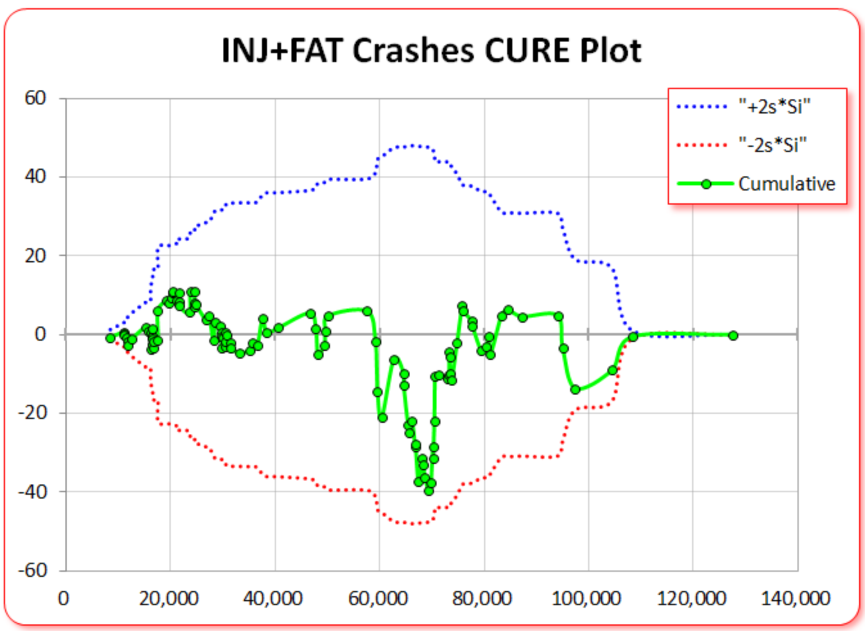

Figure 94. CURE Plot SPF - Urban Flat and Rolling 4-Lane Freeways – Fixed Object Collisions – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{(AADT^{\beta_2}) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency		Severity	
Variable	Value	Variable	Value
β_1	6.0459E+01	β_1	1.6719E+01
β_2	1.3831E+00	β_2	1.3488E+00
β_3	8.3602E+04	β_3	8.3604E+04
β_4	1.0000E+00	β_4	0.0000E+00
α	1.5799E-01	α	1.9190E-01

Figure 95. SPF Model Parameters, Urban 4-Lane Freeways – Fixed Object Collisions

Urban 4-Lane Freeways, Overturns

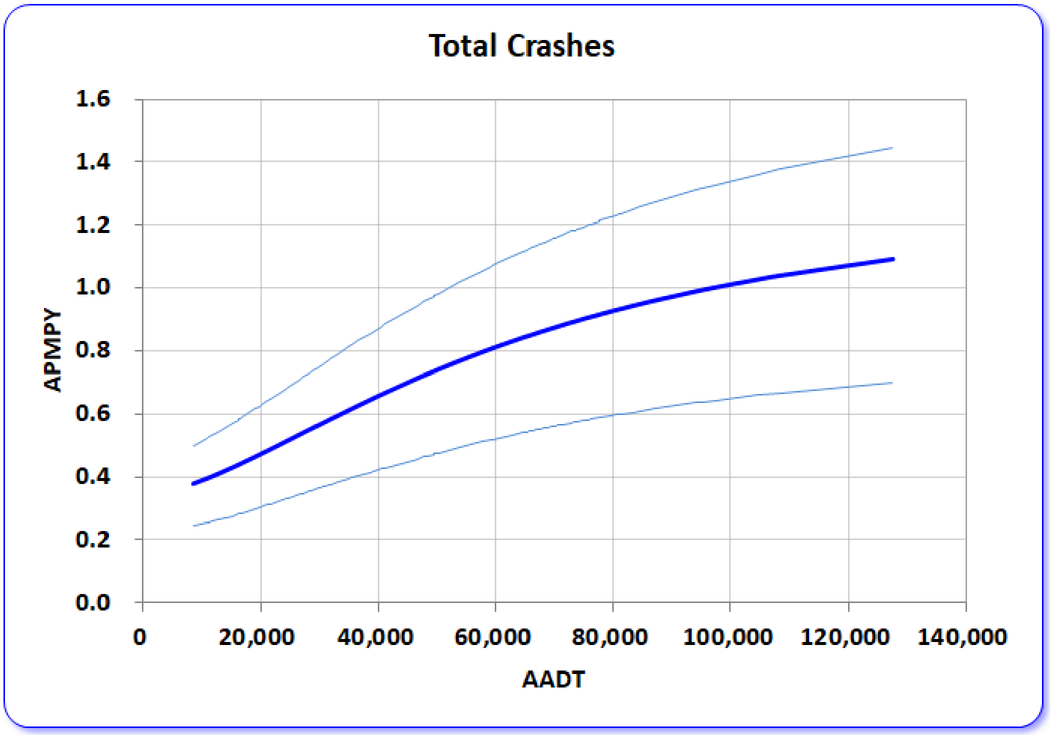

Figure 96. SPF – Urban 4-Lane Freeways – Overturns – Total Model

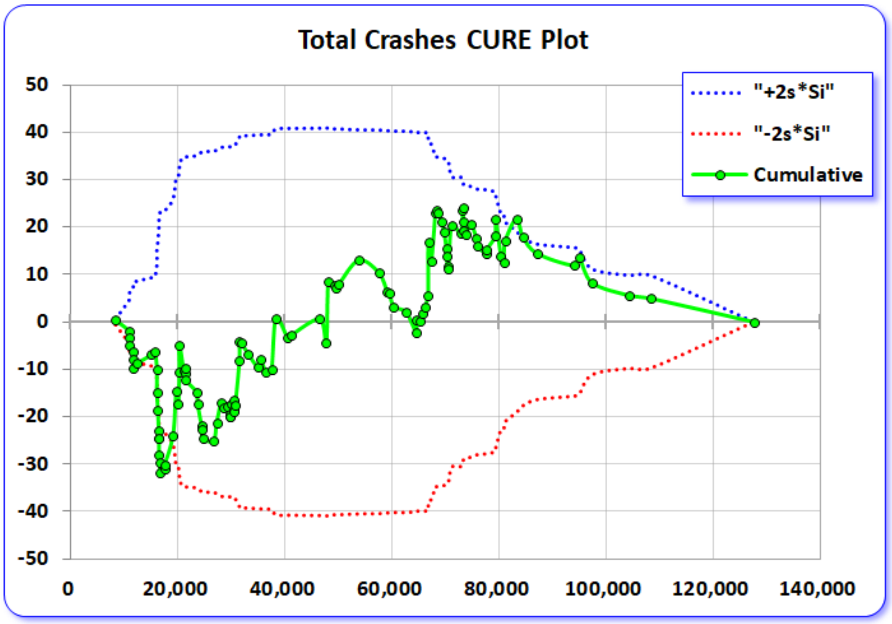

Figure 97. CURE Plot SPF - Urban 4-Lane Freeways – Overturns – Total Model

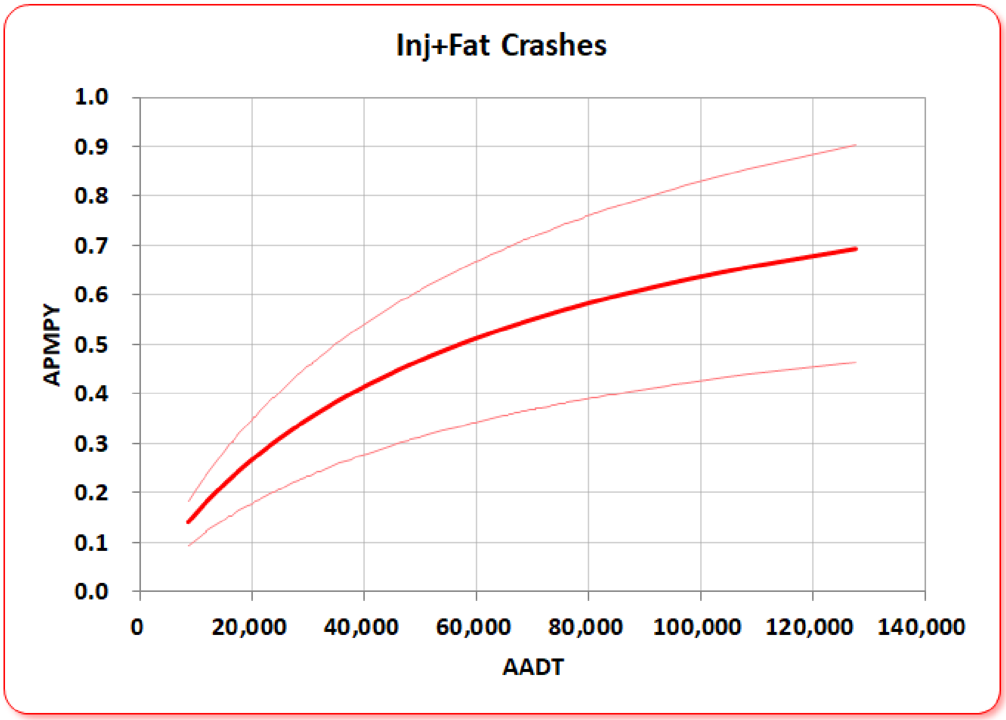

Figure 98. SPF - Urban 4-Lane Freeways – Overturns – Severity Model

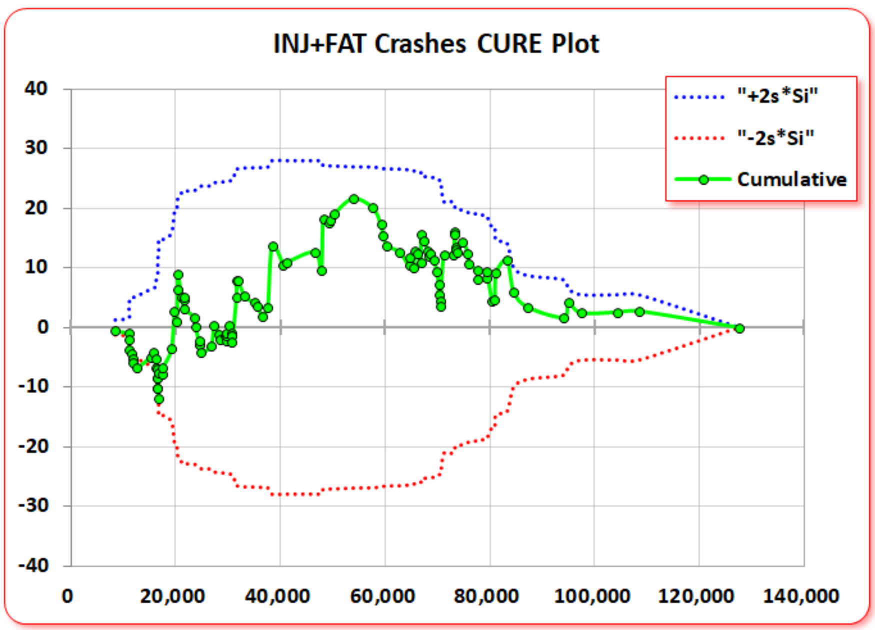

Figure 99. CURE Plot SPF - Urban 4-Lane Freeways – Overturns – Severity Model

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)\left(AADT^{\beta_2}\right)}{\left(AADT^{\beta_2}\right) + \left({\beta_3}^{\beta_2}\right)}\right)$$

$$Where\ l = Segment\ Length$$

Frequency	
Variable	Value
β_1	5.0000E+00
β_2	1.6168E+00
β_3	6.4583E+04
β_4	1.7083E+00
α	1.7511E-01

Severity	
Variable	Value
β_1	5.3128E+00
β_2	9.2592E-01
β_3	6.4583E+04
β_4	0.0000E+00
α	1.4976E-01

Figure 100. SPF Model Parameters, Urban 4-Lane Freeways – Overturns

HOW THE TWO METHODS WERE COMPARED

Diagnostics

Diagnostic methods in the context of scoping safety improvements aim to identify some abnormality or pattern in crash occurrence which may provide an important clue to an effective countermeasure. Diagnostic network screening using Crash type-specific SPFs was initially performed on all intersection and segment datasets. *95th Percentile threshold of the Gamma* distribution was used to identify locations exhibiting elevated frequency of a specific crash type for which SPF was developed. All intersections were tested for *broadsides,* rear-ends, approach turns, sideswipe-same direction. All freeway segments were tested for fixed object crashes, overturnings, rear-ends and side-swipe same direction crashes and all 2 lane highway segments were tested for fixed object crashes, overturnings, rear ends and wild animal collisions. Correction for the regression to the mean bias (RTM) was made using the Empirical Bayes (EB) procedure developed by Hauer[12]. The same datasets were then screened using binomial distribution-based Test of Proportions with stratified diagnostic norms also using 95th percentile cumulative probability threshold.

The following example demonstrates how the analysis was performed using Urban 4-Lane Divided Signalized Intersection dataset containing 188 intersections. The selected intersection has experienced 79 crashes in 5 years and 20 of them were broadsides. Average Daily Traffic (ADT) on the mainline was 30,285 and ADT on the side-road was 7,750.

SPF (Hoerl Model) developed specifically for broadside crashes at similar facilities predicts 1.57 accidents/year (APY), γ = 0.2 (coefficient needed to predict annual number of accidents when 5 years crash history was used to estimate model parameters)

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10{,}000}\beta_4}) = 1.57$$

β_1 = -1.899

β_2 = 1.959

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[12] Hauer E, D. Harwood, F. Council, M. Griffith, Estimating Safety by the Empirical Bayes Method. *In Transportation Research Record 1784*, TRB, National Research Council, Washington, D.C., 2002, pp. 126-131.

β_3 = 0.2994

β_4 = -0.5937

α = 0.2079

Correction for RTM bias using the EB procedure is performed as follows:

η_f = 20 crashes/n =20/5 = 4 crashes/year

$W_f = \frac{1}{1+\mu_f n \alpha_f} = \frac{1}{1+(1.57)(5)(0.208)} = 0.3798$

EB Frequency Estimate = $W_f \mu_f + (1 - W_f)\eta_f$

= (0.3798)1.57 + (1-0.3798)4 = 3.077 broadside crashes/year

Where

η_f – Mean number of total crashes per year over n years observed

$\alpha_f -$ Over-dispersion parameter for frequency of broadside crashes

μ_f – Total number of crashes per year predicted by the SPF

n – Number of years in the study period

W_f – Weight frequency factor

Using Excel's gamma distribution cumulative function (**Figure 101**), the cumulative probability of observing 3.077 or fewer broadside crashes per year can be computed using a definite integral as follows;

$$\Gamma\ Percentile = \int_{u=0}^{u=3.077} \frac{a^b u^{b-1} e^{-au}}{\Gamma(b)} du = 96.44\%$$

Where:

u – the mean for the facility

μ - the mean predicted by the SPF

b – shape parameter estimated from the regression ($b = 1/\alpha$)

a– b/μ (Scale parameter)

Γ– Gamma Function

In Excel, Alpha = b (1/.208 = 4.8077) and Beta = $\mu\alpha$ = 1.57(0.208) = 0.3266

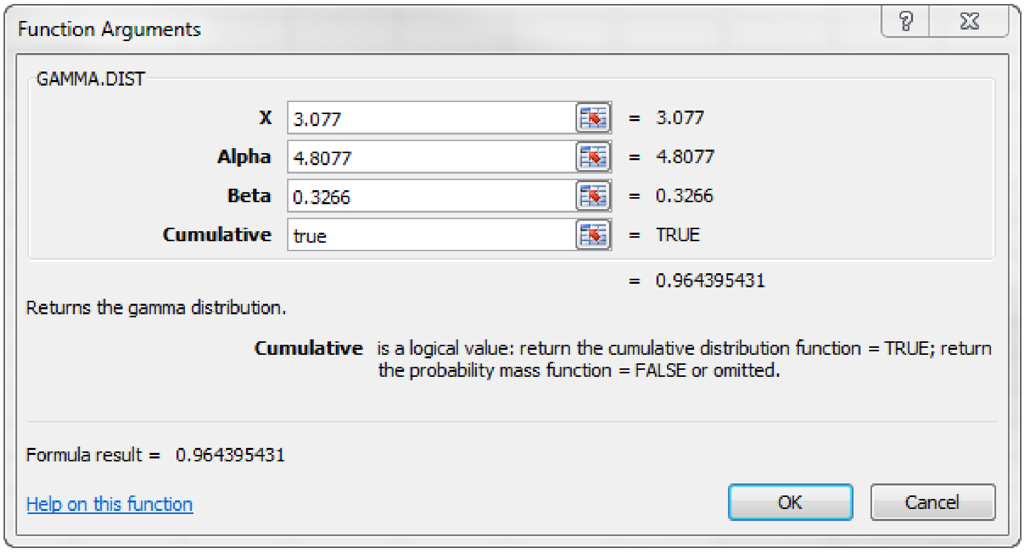

Figure 101. Gamma Distribution Cumulative Probability

The cumulative probability of ***96.43%*** suggests that the number of broadside crashes at this signalized intersection is elevated and should be examined in greater detail.

Based on Colorado statewide statistics the expected stratified percent of broadside crashes at similar intersections with ***ADT<32,000 is 14.4%.*** If 20 broadside crashes are observed out 79 total crashes, we can compute the cumulative probability of observing 20 or fewer broadside crashes as follows:

$$P(X \leq x) = B(x, n, p) = \sum_{i=0}^{x} \frac{n!}{(n-i)!i!} p^{i} (1-p)^{n-i}$$

$$P(X \leq 20, n = 79, p = 14.4\%) \approx 99.67\%$$

Where:

n – Total number of crashes (79)

x – Number of observed broadsides (20)

p – Expected % approach turn crashes based on statewide statistics (14.4%)

P – Cumulative probability of observing x, here 20, broadside crashes or fewer

The test of proportion returning 99.67 percent also indicates some degree of abnormality that should be examined further to identify a possible countermeasure.

In this case, the crash type-specific (broadside) SPF and the binomial test of proportion have produced substantially similar results, suggesting that there is a broadside problem at this intersection. *In some cases, however, crash type-specific SPFs identified sites that are not detected by the test of proportion, and in others, the test of proportion identified sites not detected by crash type-specific SPFs.* **Figures 102-105** provide Venn diagrams visually describing number of sites detected by each method and the overlap between them for 2-Lane Rural Highways; 4-Lane Urban, Freeways; 4-Lane, 4-Leg, Urban, Divided, Signalized Intersections; and Urban 4-Lane, 3-Leg, Divided, Unsignalized Intersections.

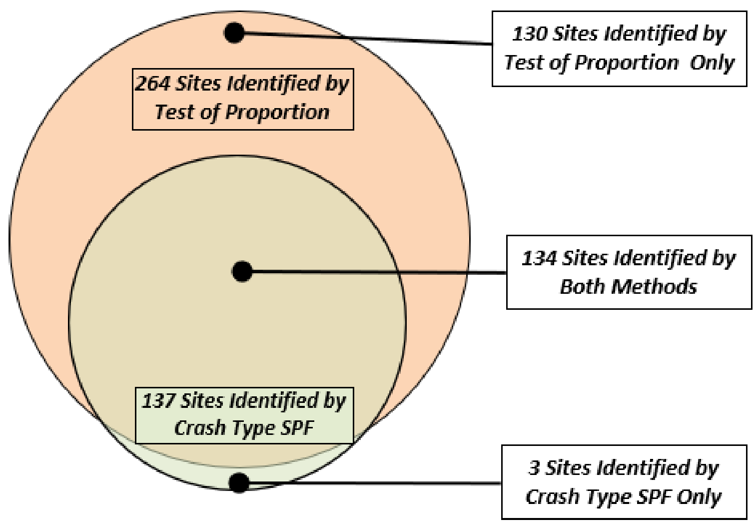

Figure 102. Venn Diagram 2 Lane Undivided Rural Highways (3971 Sites)

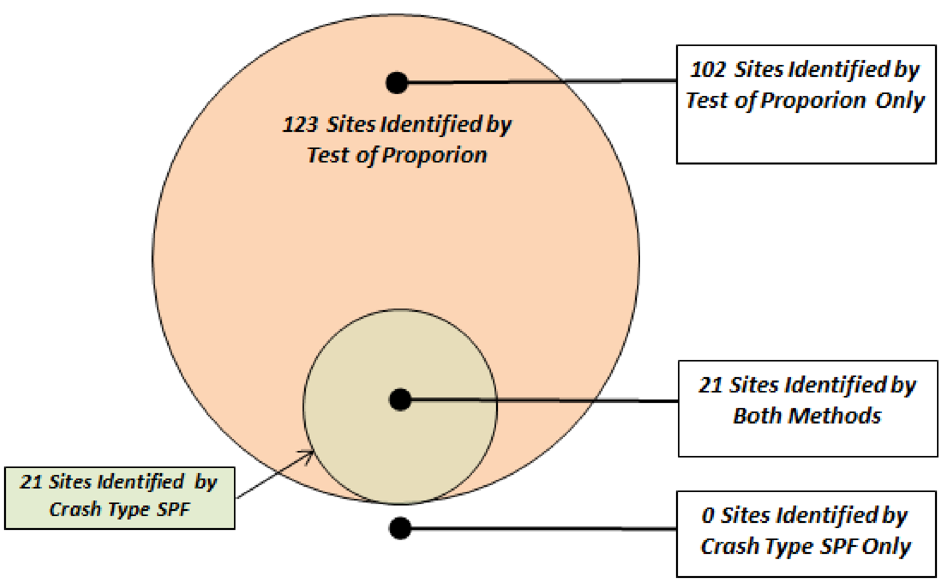

Figure 103. Venn Diagram 4 Lane Urban Freeways (230 Sites)

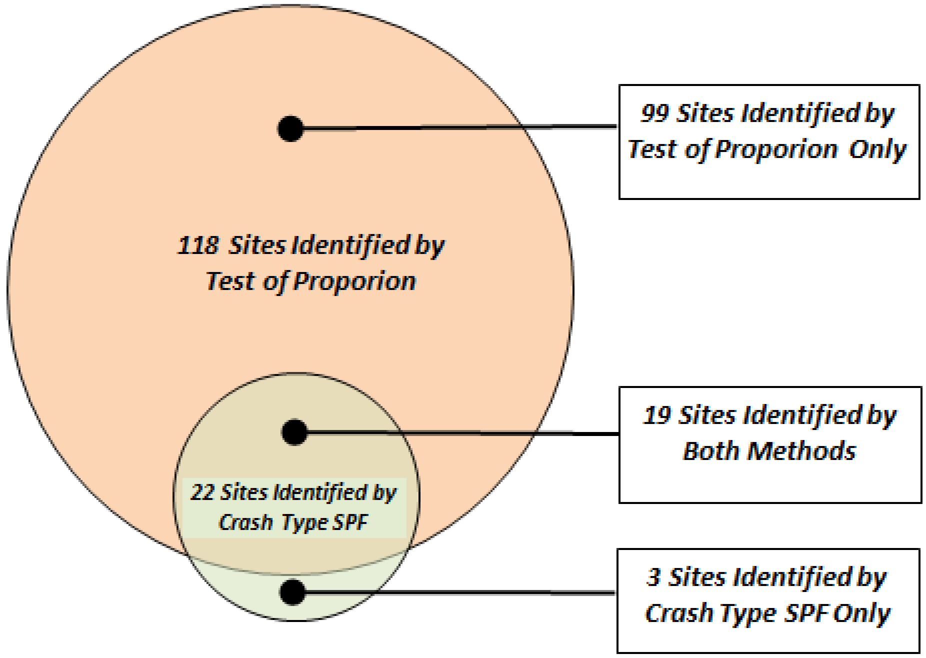

Figure 104. Venn Diagram Urban 4 Leg 4 Lane Divided Signalized Intersections (189 Sites)

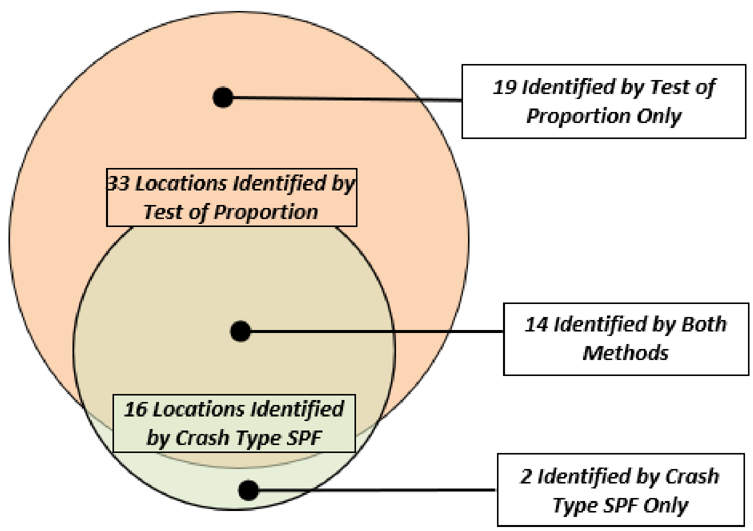

Figure 105. Venn Diagram Urban 3 Leg 4 Lane Divided Unsignalized Intersections (176 Sites)

The numbers of locations identified by each method depend on the choice of threshold. In this comparison, the 95th percentile was used for both methods as the threshold for individual crash types. The expected number of locations reported at a given threshold depends in a complex way on the method and the specifics of the models within the method. Additionally, the number of sites detected by the test of proportions was influenced by the practical rule that 5 or more crashes of a specific type or attribute must be observed over a 5-year period, otherwise the type will not contribute to identification of the location as potentially having a problem. Practitioners may adjust the threshold for either method separately to fine-tune the number of reported locations.

Initial observations suggest that the overlap between sites identified by both methods is greater for segments than for intersections. This may possibly be due to the fact that diagnostic norms for segments are stratified into 3 groups, but only 2 groups for intersections. This will need to be confirmed by further research. *Notably, in all cases when a location was identified only by the Crash Type-specific SPF it performed at LOSS-IV reflecting high potential for crash reduction from the overall frequency standpoint*. LOSS reflects how a roadway segment, or an intersection is performing in reference to the expected norm predicted by its safety performance function. The method uses EB-corrected means to enable a distinction between significant safety issues and artifacts of random fluctuation and selection bias. The degree of deviation from the norm was stratified to represent four levels of safety:

LOSS-I Low potential for crash reduction;

LOSS-II Low to moderate potential for crash reduction;

LOSS-III Moderate to high potential for crash reduc-tion; and

LOSS-IV High potential for crash reduction.

The LOSS boundaries are set by using the 20th and 80th percentiles of the gamma distribution[4].

Circumstances when Test of Proportions Using Stratified Diagnostic Norms Fails to Detect Crashes Identified by Crash Type SPF

Following the examination of sites detected by crash type-specific SPFs only, we identified general circumstances when this occurs. When two or more major crash types are concurrently over-represented, the number of all crashes will often be elevated without upsetting the balance of proportions among crash types. Such events happen infrequently, but of course they cannot be detected by a test of proportion. When performing the diagnostic Test of Proportions, it is important to assess the magnitude of the safety problem using SPFs for all crashes in aggregate. Doing so will guard against overlooking locations with the property described above. In highway safety diagnostics, as in medicine, it is always a good practice to evaluate overall health of the patient when screening for specific pathologies.

The following case history is typical of locations where crash type-specific SPFs detected a problem and Test of Proportions did not. This 4-lane, 4-leg, urban, divided signalized intersection (**Figure 106**) shows high potential for crash reduction from the overall crash frequency standpoint reflected by the Level of Service of Safety-IV (**Figure 107**).

Figure 106. Urban 4-Lane, 4-Leg, Divided, Signalized Intersection

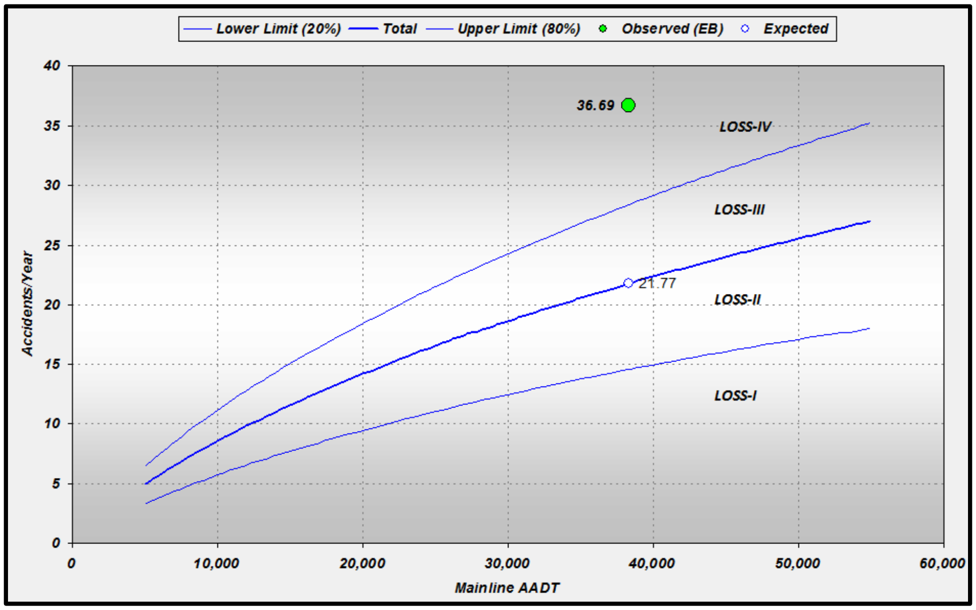

Figure 107. EB Corrected Intersection Frequency SPF

Distribution of crashes by type is provided in **Figure 107.**

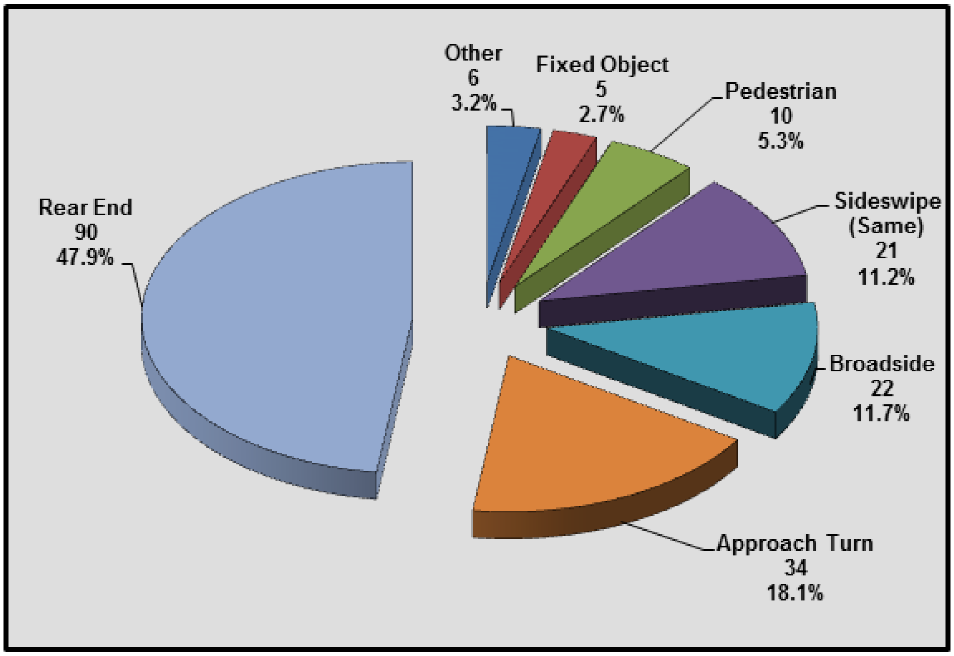

Figure 108. Distribution of Crashes by Type

Results of diagnostic tests using the same notation as in previous examples are as follows:

Rear Ends $P(X \leq 90, n = 188, p = 56.04\%)$ = 2.46%

Approach Turns $P(X \leq 34, n = 188, p = 15.76\%)$ = 83.93%

Broadsides $P(X \leq 22, n = 188, p = 10.35\%)$ = 77.20%

Where:

n – Total number of crashes (188)

x – Number of observed crashes (90 rear ends, 34 approach turns, 22 broadsides)

p – Expected % of crashes based on statewide statistics (56.04% rear end, 15.76% approach turn and 10.35% broadside)

P – Cumulative probability of observing X crashes of specific type or fewer

The test results show that none of the crash types exceeded the 95th percentile on the Test of Proportions, using stratified diagnostic norms, yet the overall frequency of crashes is well above the mean predicted by the all-crash SPF.

We will now examine the gamma distribution percentile using crash type-specific SPFs;

For ADTs: 38,310 (mainline) and 24,500 (side-road).

Broadsides:

SPF (Hoerl Model) developed specifically for broadside crashes at similar facilities predicts 2.17 accidents/year (APY)

$$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4}) = 2.17$$

The model parameters can be found in **Table B** and are as follows:

B_1 = -18.99

B_2 = 1.959

B_3 = 0.2994

B_4 = -0.5937

α = 0.2079

γ = 0.2

There were 22 broadside crashes at this intersection over the 5-year period from 2012 to 2016. Correction for the RTM bias using the EB procedure is performed as follows:

η_f= 22 crashes/n =22/5 = 4.4 crash/year

$$W_f = \frac{1}{1+\mu_f n \alpha_f} = \frac{1}{1+(2.17)(5)(0.2079)} = 0.3072$$

EB Frequency Estimate = $W_f \mu_f + (1 - W_f)\eta_f$

= (0.3072)2.17 + (1-0.3072)4.4 = 3.715 broadside crashes/year

Cumulative probability of observing 3.715 or fewer broadside crashes per year can be computed using definite integral of the gamma probability density function as follows:

$$\Gamma\ Percentile = \int_{u=0}^{u=3.715} \frac{a^b u^{b-1} e^{-au}}{\Gamma(b)} du = 92.49\%$$

Where: μ = 2.17, $b = 1/\alpha$ = 4.812, a = b/μ = 0.451 and Γ– Gamma Function

Approach Turns:

SPF (Hoerl Model) developed specifically for approach turn crashes at similar facilities predicts 2.33 accidents/year (APY)

$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$= = 2.33

The model parameters can be found in **Table B** and are as follows:

β_1 = -14.70

β_2 = 1.669

β_3= 0.0897

β_4 = -0.3515

α = 0.6213

There were 34 approach turn crashes in the 5-year period from 2012 to 2016. Correction for the RTM bias using the EB procedure is performed as follows:

η_f= 34 crashes/n =34/5 = 6.80 crashes/year

$$W_f = \frac{1}{1 + \mu_f n \alpha_f} = \frac{1}{1 + (2.33)(5)(0.6213)} = 0.1214$$

EB Frequency Estimate = $W_f \mu_f + (1 - W_f)\eta_f$

= (0.1214)2.33 + (1-0.1214)6.80 = 6.257 approach turn crashes/year

As above, the cumulative probability of observing 6.257 or fewer approach turn crashes per year can be computed using definite integral of the gamma probability density function:

$$\Gamma\ Percentile = \int_{u=0}^{u=6.257} \frac{a^b u^{b-1} e^{-au}}{\Gamma(b)} du = 95.89\%$$

Where: μ = 2.33, $b = 1/\alpha$ = 1.609, a = b/μ = 0.6906 and Γ– Gamma Function

At this intersection approach turn crashes (Gamma percentile 95.89%) and broadsides (Gamma percentile 92.49%) are elevated, yet proportions between crash types are approximately preserved and thus the problems cannot be detected by the binomial test. *An important clue that something is wrong, however, is provided by the fact that overall safety performance at this intersection is at LOSS-IV frequency reflecting high potential for crash reduction.* The approach turn problem could be explained by the permitted-protected left turn phasing, and possibly short *yellow plus all red intervals* can account for the elevated broadsides.

Circumstances when Crash Type SPFs Fail to Detect Problems Identified by the Test of Proportions

In many cases Test of Proportions using stratified diagnostic norms reveals the existence of crash patterns susceptible to correction that are not detected either by aggregate SPFs or crash type-specific SPFs. As was initially observed in (1), the existence of accident patterns susceptible to correction may or may not be accompanied by elevation in overall frequency of crashes. Here we see that these patterns may also occur without elevation in frequency of any specific crash type.

The following case history is typical of locations where the Test of Proportions identified a problem, but crash type SPFs did not. This urban 4-lane divided freeway segment performs at LOSS-II, reflecting only low to moderate potential for crash reduction from the overall crash frequency standpoint (**Figure 109**). The Test of Proportions, however, shows a strong pattern of fixed object crashes. They represent 6 out of 11 crashes (**Figure 110**).

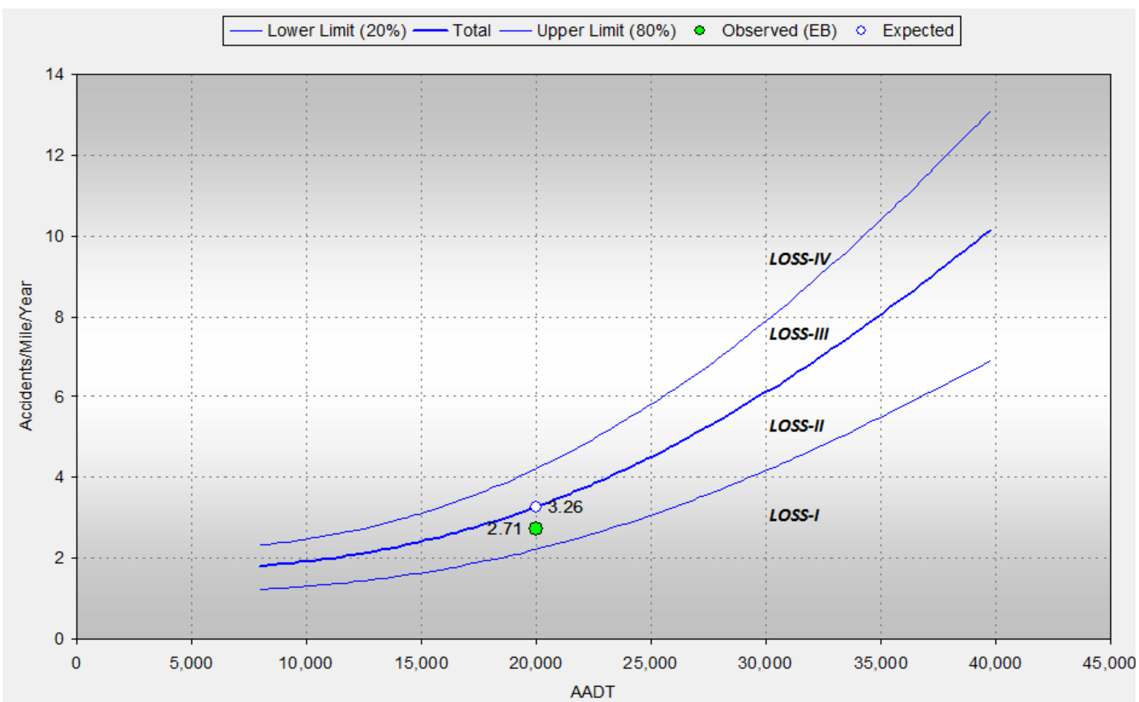

Figure 109. EB Corrected Freeway Frequency SPF

Test of proportion shows that the resulting cumulative probability is nearly 100% (p = 12.4% for ADT<50,000). None of the crashes involved collisions with a guard rail, (**2 fence, 1 sign, 2 trees**

and 1 embankment). This suggests that fixed objects should be removed from the clear zone adjacent to the traveled way or shielded by a longitudinal barrier.

Fixed Object $P(X \leq 6, n = 11, p = 12.4\%)$ = 100%

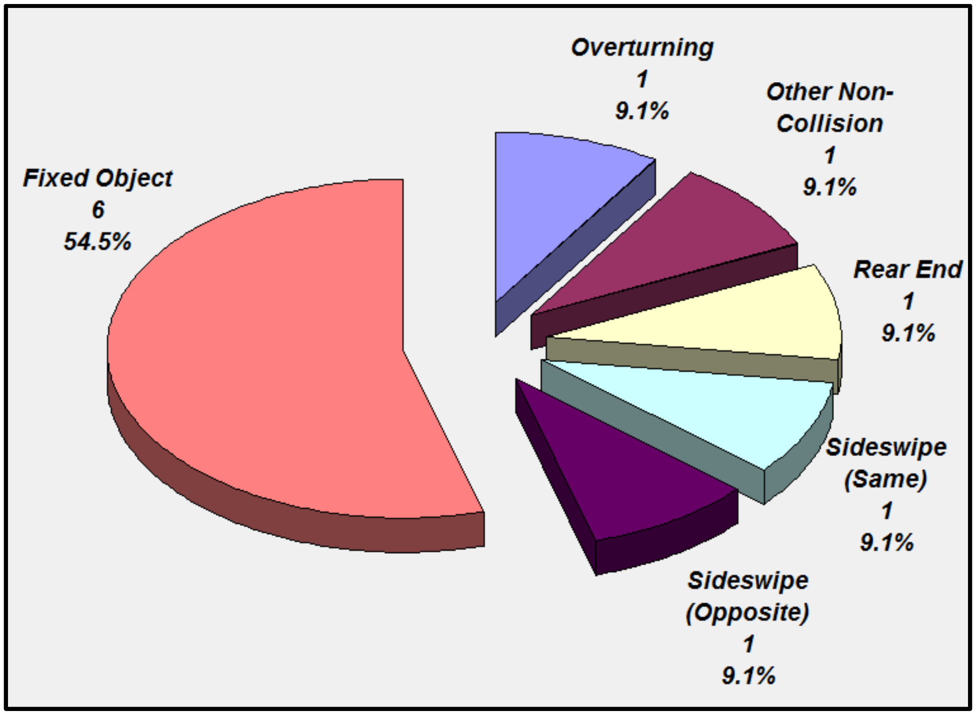

Figure 110. Crash Distribution by Type

We will now examine the Gamma percentile for fixed object crashes using the crash type-specific SPF:

AADT=19,600 and length=0.88 mile

<u>Fixed objects: </u> SPF (Sigmoid Model) developed specifically for fixed object crashes at similar facilities predicts 1.63 accidents/mile/year (APMY)

$$APMPY_{Sigmoid} = (\gamma)(l)\left(\beta_4 + \frac{(\beta_1)(AADT^{\beta_2})}{(AADT^{\beta_2}) + (\beta_3{}^{\beta_2})}\right) = 1.63$$

Model parameters can be found in **Table B** and are also listed below:

β_1 = 60.458

β_2 = 1.3831

β_3 = 83,602

β_4 = 1.000

α = 0.1580

There were 6 fixed object crashes on this 0.88-mile section of highway in the 5-year period from 2012 to 2016. Correction for the RTM bias using the EB procedure is performed as follows:

η_f= 6 crashes/*exposure*/n =6/0.88/5 = 1.36 crashes/mile/year

$$W_f = \frac{1}{1+\mu_f n \alpha_f} = \frac{1}{1+(1.63)(5)(0.1580)} = 0.4371$$

EB Frequency Estimate = $W_f \mu_f + (1 - W_f)\eta_f$

= (0.4371)1.63 + (1-0.4371)1.36 = 1.478 fixed object crashes/mile/year.

The cumulative probability of observing 1.48 or fewer fixed object crashes per year is computed using definite integral of the gamma probability density function as follows:

$$\Gamma\ Percentile = \int_{u=0}^{u=1.478} \frac{a^b u^{b-1} e^{-au}}{\Gamma(b)} du = 45.70\%$$

Where:

μ = 1.63, $b = 1/\alpha$ = 6.329, $a = b/\mu$ = 3.883, Γ– Gamma Function

This shows that frequency of fixed object crashes is slightly below the mean (45.7 percentile) predicted by the fixed object crash SPF, yet there is a crash pattern susceptible to correction detected by the diagnostic test of proportions.

Network Screening

Network screening, in contrast with diagnostics, aims to identify sites exhibiting some potential for crash reduction, also as known as "sites with promise"[13]. This potential may be reflected by elevated aggregate frequency or severity of crashes, presence of crash type patterns or attributes (icy road for example) or both. Since 2000 CDOT has been using a combination of aggregate SPFs and test of proportions with stratified diagnostic norms to conduct network screening. If a site showed either elevated frequency, severity or an abnormal crash pattern it would be retained for further examination.

To compare the effectiveness of network screening using Crash type-specific SPFs with CDOT's present methodology, screening using new Crash type-specific SPFs was initially performed on all intersection and segment datasets. The 80th *Percentile threshold of the Gamma* distribution (boundary line between LOSS-III and LOSS-IV) was used to identify locations exhibiting elevated frequency and severity of a specific crash type for which SPF was developed. All intersections were tested for broadsides, rear-ends, approach turns, sideswipe-same direction. All freeway segments were tested for fixed object crashes, overturnings, rear-ends and side-swipe same direction crashes and all 2-lane highway segments were tested for fixed object crashes, overturnings, rear ends and wild animal collisions. Correction for the regression to the mean bias (RTM) was made using the Empirical Bayes (EB) procedure developed by Hauer[12]. The same datasets were then screened using binomial distribution-based Test of Proportions with stratified diagnostic norms with 95th percentile cumulative probability threshold and aggregate SPFs for frequency and severity using 80th *Percentile threshold of the Gamma* distribution (boundary line between LOSS-III and LOSS -IV).

The following example demonstrates how the analysis was performed on Urban 4-Lane Divided Signalized Intersection dataset containing 188 intersections. The selected intersection (**Figure 111**) has experienced 131 crashes in 5 years and 30 of them were approach turns. Average Daily Traffic (ADT) on the mainline was 26,500 and ADT on the side-road was 26,400.

[13] Hauer, E., Kononov, J., and Griffith, M Screening the Road Network for Sites with Promise. In Transportation Research Record 1784, TRB, National Research Council, Washington, D.C., 2002 pp 27-42.

Figure 111. Urban 4-Lane, 4-Leg, Divided, Signalized Intersection

SPF (Hoerl Model) developed specifically for approach turn crashes at similar facilities predicts 1.57 accidents/year (APY), γ = 0.2 (coefficient needed to predict annual number of accidents when 5 years crash history was used to estimate model parameters)

$APY_{Hoerl} = (\gamma)(EXP^{\beta_1})(AADT_{Major}{}^{\beta_2})(AADT_{Minor}{}^{\beta_3})(EXP^{\frac{AADT_{Major}}{10,000}\beta_4})$= 1.96

β_1 = -1.4699E+01

β_2 = 1.6690E+00

β_3 = 8.9693E-02

β_4 = -3.5149E-01

α = 0.621

Correction for RTM bias using the EB procedure is performed as follows:

η_f= 30 crashes/n =30/5 = 6 crashes/year

$W_f = \frac{1}{1+\mu_f n \alpha_f} = \frac{1}{1+(1.96)(5)(0.621)} = 0.141$

EB Frequency Estimate = $W_f \mu_f + (1 - W_f)\eta_f$

= (0.141)1.96 + (1-0.141)6 = 5.43 broadside crashes/year

Where

η_f – Mean number of total crashes per year over n years observed

α_f − Over-dispersion parameter for frequency of broadside crashes

μ_f – Total number of crashes per year predicted by the SPF

n – Number of years in the study period

W_f – Weight frequency factor

Using Excel's gamma distribution cumulative function (**Figure 112**), cumulative probability of observing 3.077 or fewer approach turn crashes per year can be computed using definite integral as follows:

$$\Gamma\ Percentile = \int_{u=0}^{u=5.43} \frac{a^b u^{b-1} e^{-au}}{\Gamma(b)} du = 96.4\%$$

Where:

u – the mean for the facility

μ - the mean predicted by the SPF

b – shape parameter estimated from the regression ($b = 1/\alpha$)

a– b/μ (Scale parameter)

Γ– Gamma Function

In Excel, Alpha = b (1/.621 = 1.61) and Beta = $\mu\alpha$ = 1.96(0.621) = 1.217

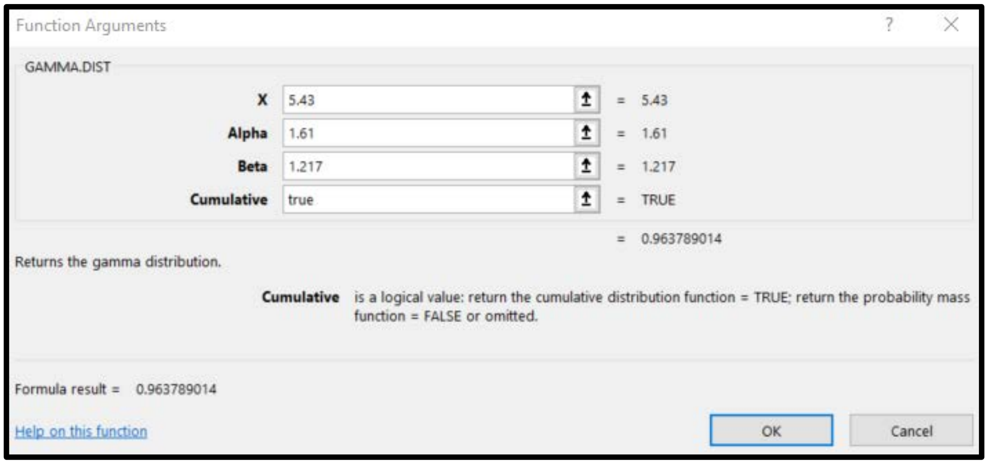

Figure 112. Gamma Distribution Cumulative Probability

A cumulative probability of ***96.4%*** suggests that the number of approach turn crashes at this signalized intersection is elevated and should be examined in greater detail.

Based on Colorado statewide statistics the expected stratified percent of approach turn crashes at similar intersections with ***ADT<32,000 is 16%.*** If 30 approach crashes are observed out 131 total crashes, we can compute the cumulative probability of observing 30 of fewer broadside crashes as follows:

$P(X \leq x) = B(x, n, p) = \sum_{i=0}^{x} \frac{n!}{(n-i)!i!} p^i (1-p)^{n-i}$

$P(X \leq 30, n = 131, p = 16\%) = 98.5\%$

Where:

n – Total number of crashes (131)

x – Number of observed broadsides (30)

p – Expected % approach turn crashes based on statewide statistics (16%)

P – Cumulative probability of observing x, here 30, approach turn crashes or fewer

The Test of Proportion returning 98.5 percentile also indicates some degree of abnormality in frequency of approach turns that should be examined further to identify a possible countermeasure.

Results of the aggregate SPF/LOSS (**Figures 113-114**) analysis show that overall safety performance of this intersection is at LOSS-IV reflecting high potential for crash reduction from the frequency and severity standpoints.

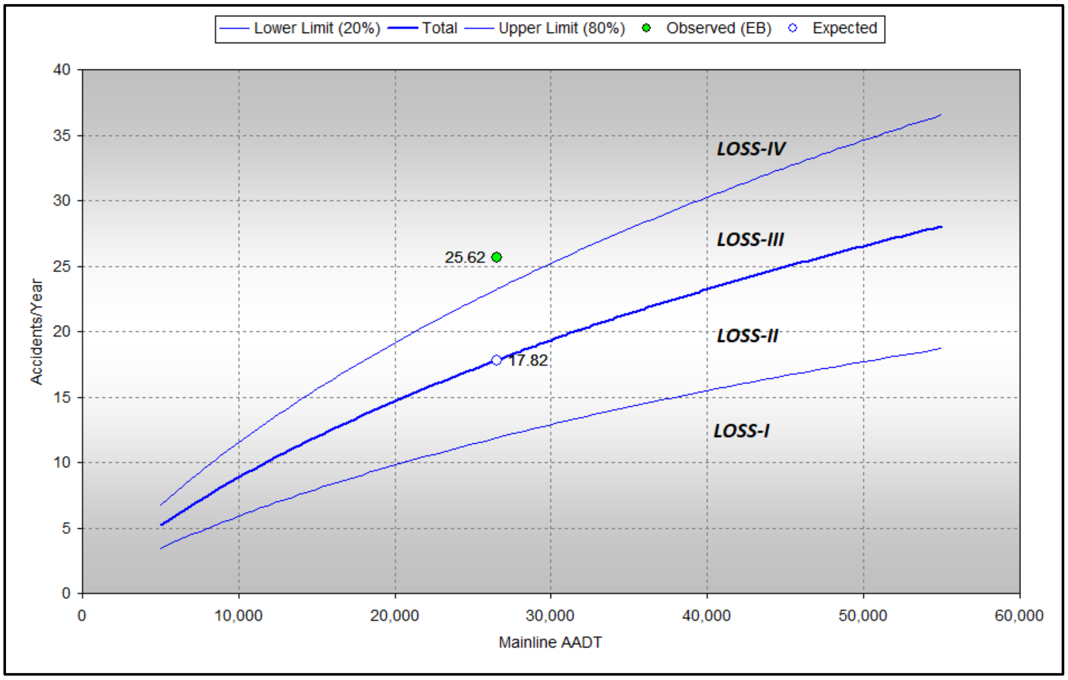

Figure 113. EB Corrected SPF Aggregate Frequency Graph

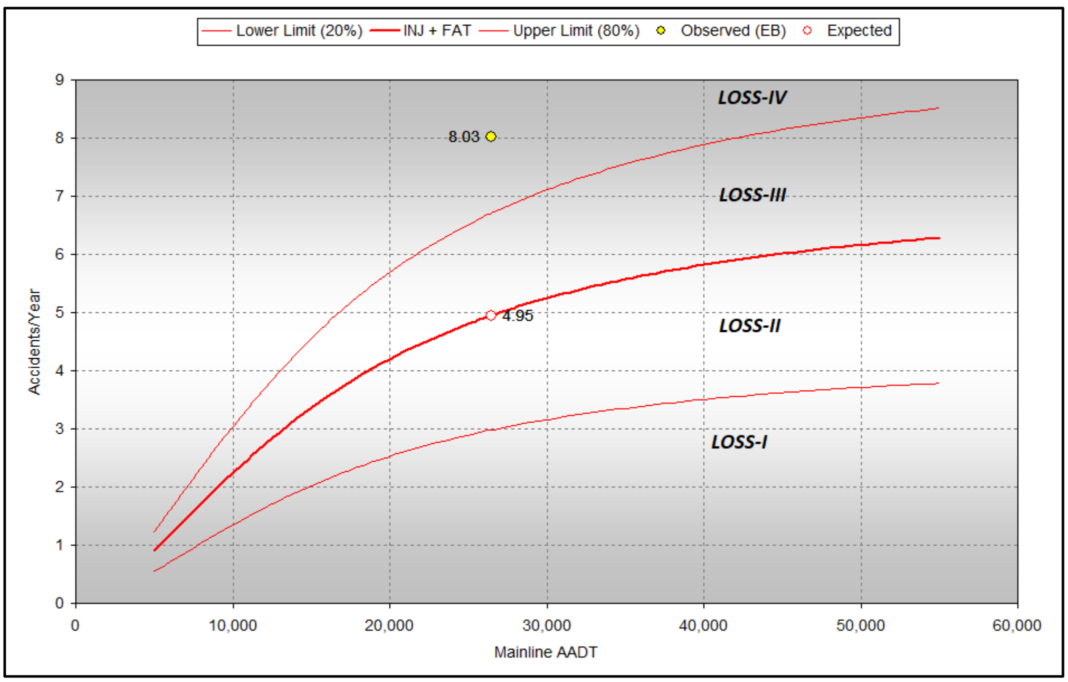

Figure 114. EB Corrected SPF Aggregate Severity Graph

In this case, crash type-specific (approach turn) SPF and binomial test of proportions have produced substantially similar results, flagging this intersection as a site with promise. Aggregate

SPF analysis also showed that this location has high potential for crash reduction. From the standpoint of network screening, CDOT's current methodology, using aggregate SPF in concert with the stratified test of proportions, would flag this location for further examination. In this particular case CDOT's current network screening methodology is sufficient to identify a site with promise, without using crash type-specific SPF.

In some cases, however, crash type-specific SPFs identifies sites that are not detected by the test of proportion, and in others, test of proportion identifies sites are not detected by crash type-specific SPFs. In most, but not all, cases, when conducting network screening, if a location is flagged by the crash type SPF, and missed by the test of proportions, it would be detected by the aggregate SPFs. **Figures 115-122** provide Venn diagrams visually describing number of sites identified by each method and the overlap between them for 2-Lane Rural Highways; 4-Lane Urban Freeways; 4-Lane, 4-Leg, Urban, Divided, Signalized Intersections; and Urban 4-Lane, 3-Leg, 4-Lane, Divided, Unsignalized Intersections. Initially, screening methods are compared using frequency only crash type SPFs, and then comparison is performed using crash type frequency and also severity SPFs. Under each Venn diagnram we made an observation as to how many of the sites missed by the test of proportion are not in the aggregate LOSS-IV category.

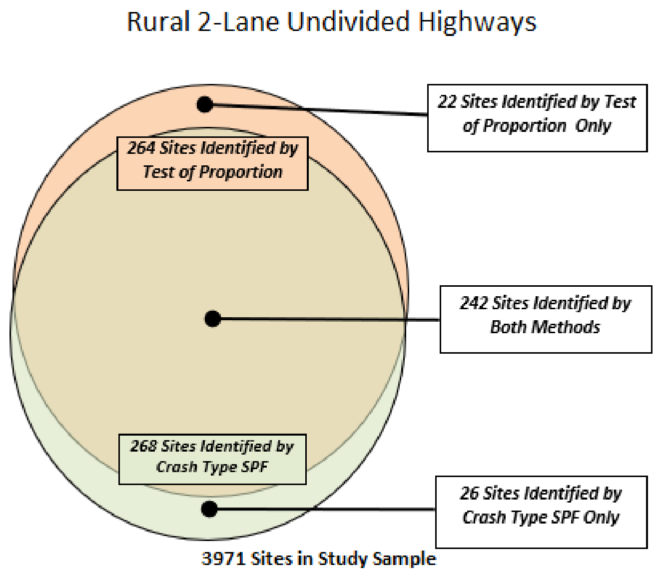

Figure 115. Venn Diagram of Comparing Network Screening Methods using Frequency Crash Type SPFs 2-Lane Rural Highways

Out of the 26 Locations only identified by Crash Type SPFs, **all but 1** were in the aggregate LOSS-IV category.

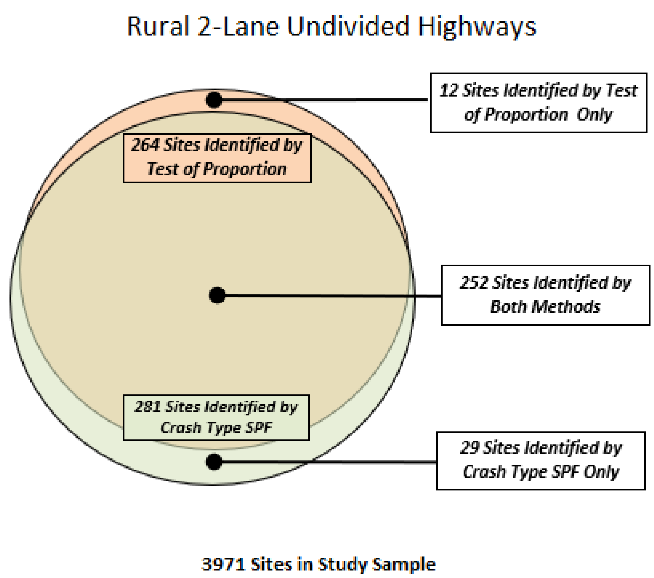

Figure 116. Venn Diagram of Comparing Network Screening Methods Using Both Frequency and Severity Crash Type SPFs 2-Lane Rural Highways

Out of the 29 Locations only identified the by Crash Type SPFs, all but 4 were in aggregate SPFs LOSS-IV category.

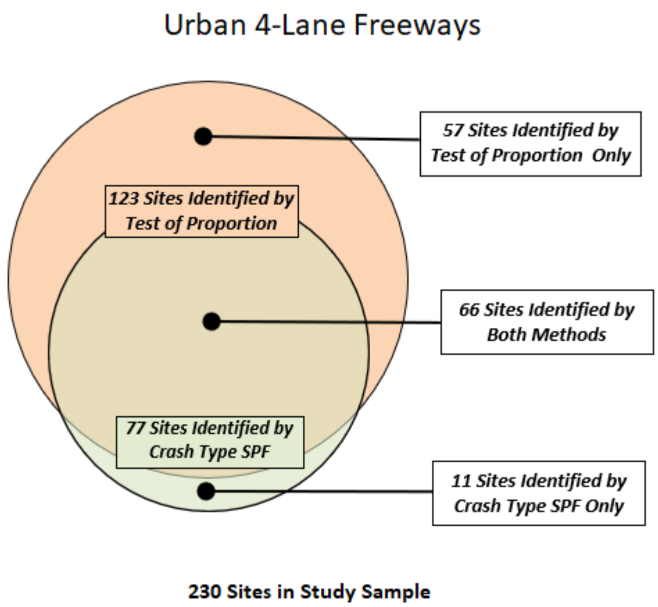

Figure 117. Venn Diagram of Comparing Network Screening Methods using Frequency Crash Type SPFs Urban 4 Lane Freeways

All 11 locations only identified by the Crash Type SPFs are in the aggregate SPFs LOSS-IV category.

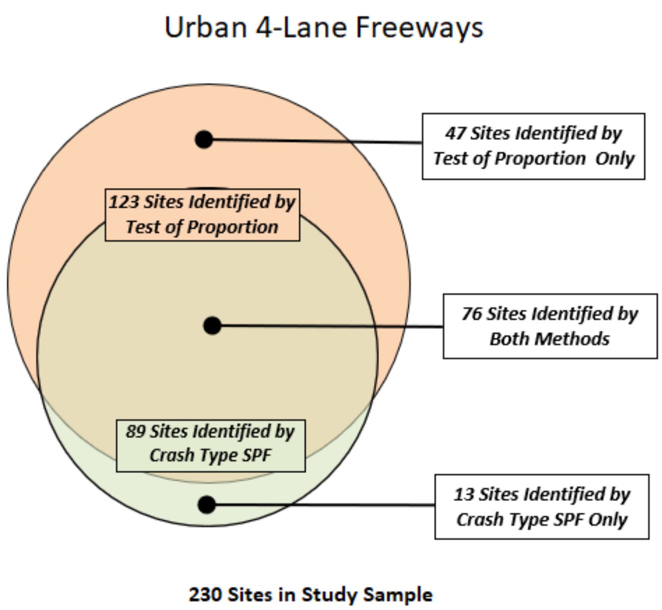

Figure 118. Venn Diagram of Comparing Network Screening Methods Using Both Frequency and Severity Crash Type SPFs Urban 4 Lane Freeways

Out of the 13 Locations only identified by the Crash Type SPFs, **all but one** was in the aggregate SPF LOSS-IV category.

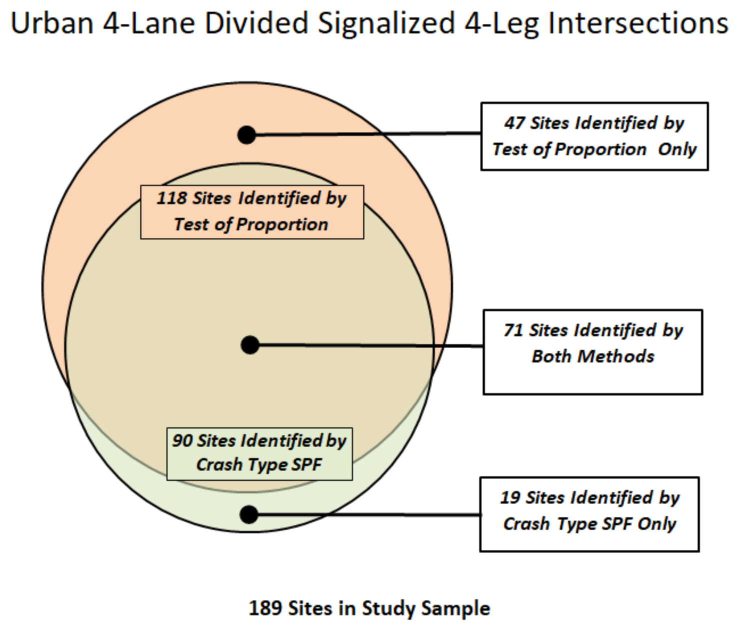

Figure 119. Venn Diagram of Comparing Network Screening Methods Using Frequency Crash Type SPFs, Urban 4-Lane, 4-Leg, Divided, Signalized Intersections

Out the 19 Locations only identified the by the Crash Type SPFs, 13 were in the aggregate SPF LOSS-IV category

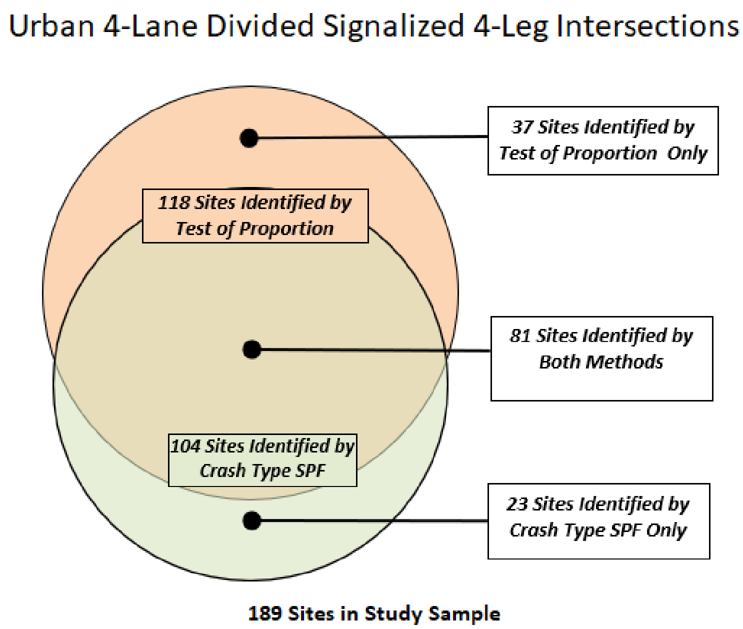

Figure 120. Venn Diagram of Comparing Network Screening Methods Using Both Frequency and Severity Crash Type SPFs Urban 4-Lane, 4-Leg, Divided, Signalized Intersections

Out of the 23 Locations identified only by the Crash Type SPFs (**Figure 118**) 13 were in the aggregate SPF LOSS-IV category.

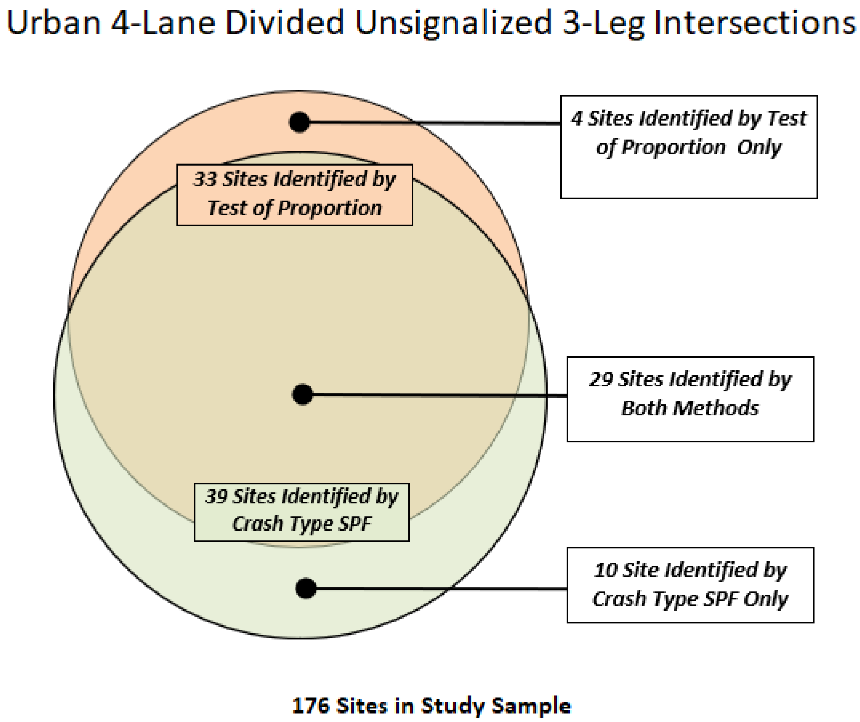

Figure 121. Venn Diagram of Comparing Network Screening Methods Using Frequency Crash Type SPFs Urban 4-Lane, 3-Leg, Divided, Unsignalized Intersections

All 10 Locations only identified by Crash Type SPFs were in the aggregate SPF LOSS-IV category.

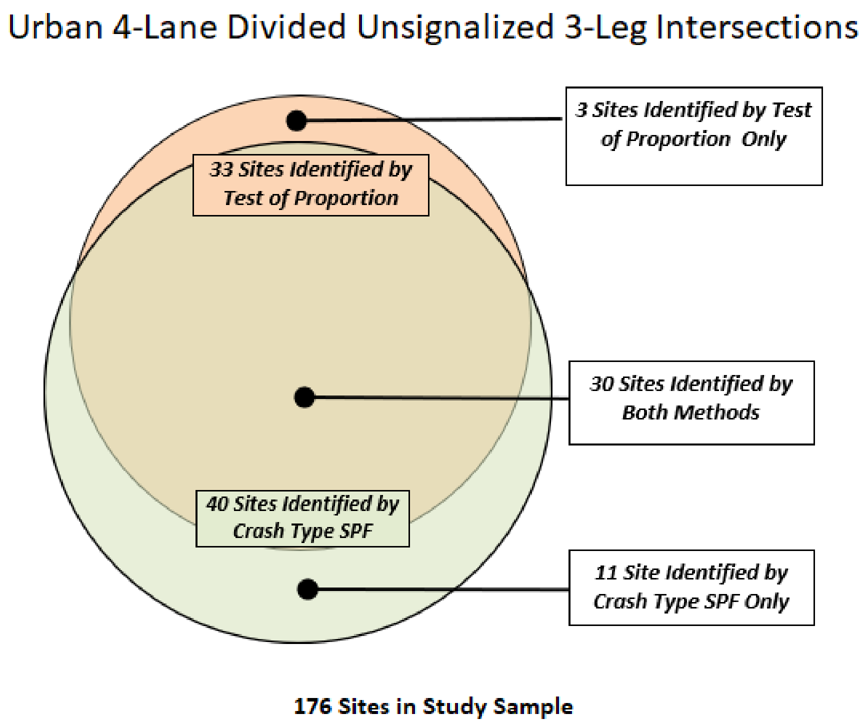

Figure 122. Venn Diagram of Comparing Network Screening Methods Using Both Frequency and Severity Crash Type SPFs Urban 4-Lane, 3-Leg, Divided, Unsignalized Intersections

All 11 Locations only identified by Crash Type SPFs were found to be in the aggregate SPF LOSS-IV category.

In the course of this study we observed that test of proportion presently does not have a capability to detect elevated crash severity of a specific crash type. It only tests for elevated aggregate severity and overrepresentation in frequency of a specific crash type or attribute. It is possible that in some rare cases specific crash type at a location may exhibit average frequency, but elevated severity. These infrequent circumstances may be missed by test of proportion and not always reflected by the aggregate SPFs. An effective strategy to remedy the situation is to develop stratified diagnostic norms for injury and fatal crashes only and to introduce injury focused level of diagnostic tests in addition to presently used tests for crashes of all severity. For example, distribution by crash type for Urban 4-Lane, 4-Leg, Divided, Signalized Intersections for injury and fatal only crashes is provided in **Figure 123**, and for comparison purposes similar distribution for all crashes is provided in **Figure 124**. Not surprisingly percent of approach turns, broadsides and pedestrian crashes is increased while percent of rear-ends and sideswipes decreased when injury only crashes are considered.

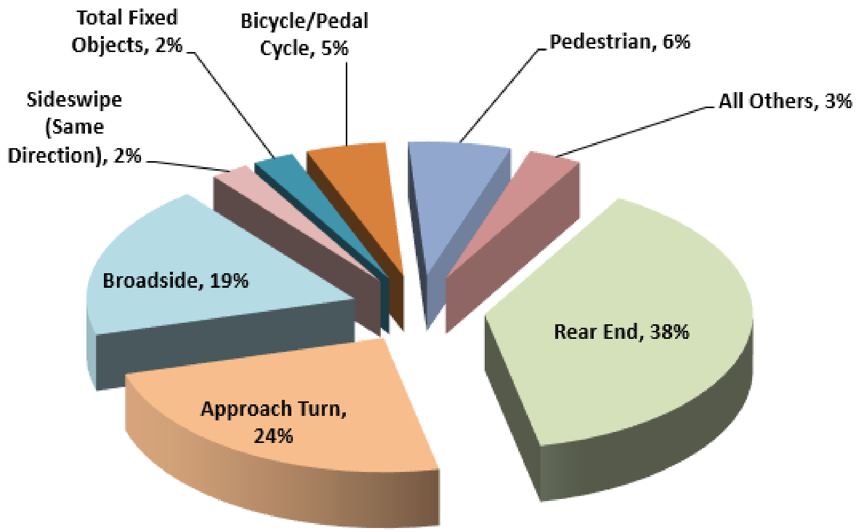

Figure 123. Distribution of Injury Crashes by Type Urban 4-leg Divided Signalized Intersections with ADT<32,000

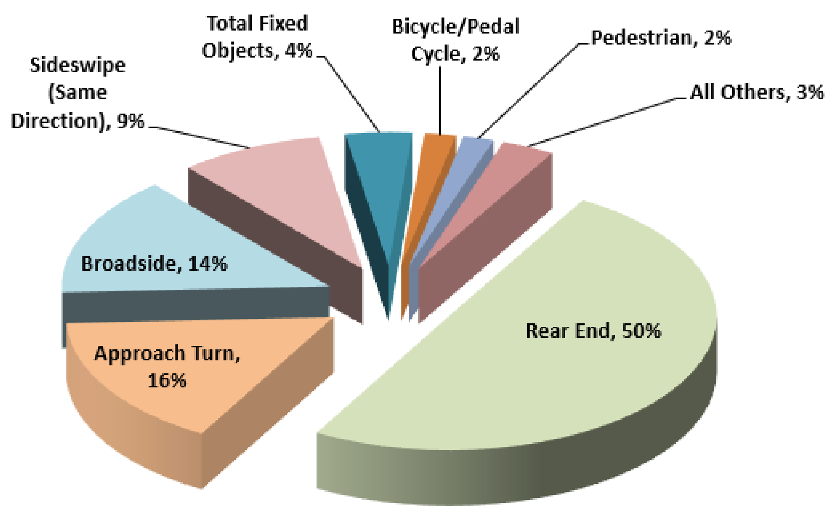

Figure 124. Distribution of All Crashes by Type Urban 4-leg Divided Signalized Intersections with ADT<32,000

Distribution of injury only crashes by type can be effectively used to detect elevated severity of a specific crash type at Urban 4-Lane, 4-Leg, Divided, Signalized Intersections or any other facility using test of proportion even if its frequency is average.

CONCLUSIONS

Diagnostic methods in the context of scoping safety improvements aim to identify some abnormality or pattern in crash occurrence which may provide an important clue to an effective countermeasure. Network screening in contrast with diagnostics aims to identify sites exhibiting some potential for crash reduction, also as known as “sites with promise”. This potential may be reflected by elevated aggregate frequency or severity of crashes, presence of crash type patterns or attributes or both.

The comparative analysis of network and diagnostic screenings using combined test of proportions based on stratified diagnostic norms in concert with aggregate SPF/LOSS analysis and using crash type-specific SPFs shows that present CDOT methodology is highly effective. Both methods, however, have some vulnerabilities that need to be addressed.

During diagnostic screening we observed that in some rare cases when two or more major crash types are concurrently elevated the overall number of crashes may be elevated *without upsetting the balance of proportions among crash types.* Such events happen infrequently but can’t be detected by a test of proportions. For this reason, the diagnostic Test of Proportions should be supplemented with assessment of the magnitude of the safety problem using assessment of the aggregate LOSS levels. In addition to providing an important context for the diagnostic examination, doing so effectively guards against failing to identify locations having multiple crash types with elevated frequencies. In this study all locations identified by the Crash Type-specific SPF at 95th percentile threshold but not diagnostic Test of Proportions performed at LOSS-IV reflecting high potential for crash reduction from the overall frequency or severity standpoints.

In the course of this study we observed that test of proportion presently does not have a capability to detect elevated crash severity of a specific crash type. It only tests for elevated aggregate severity and overrepresentation in frequency of a specific crash type or attribute. It is possible that in some rare cases specific crash type at a location exhibits average frequency, but elevated severity. These infrequent circumstances may be missed by test of proportion and not always reflected by the aggregate SPFs. An effective strategy to remedy the situation is to develop stratified diagnostic norms for injury and fatal crashes only and to introduce injury focused level of diagnostic tests in addition to presently used tests for crashes of all severity.

CDOT presently uses 13 segment and 25 intersection SPF frequency and severity models. If development of crash type-specific SPFs is contemplated, it would require development of an additional 152 frequency and severity models (assuming 4 major crash types per facility) which would need to be re-estimated every five years or so to reflect changes in safety performance. Considering that CDOT's present methodology is highly effective, the additional effort of estimating 152 new models and maintaining them is not justified.