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SAFETY PERFORMANCE FUNCTIONS FOR RAMP TERMINALS AT DIAMOND INTERCHANGES

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16. Abstract

This report documents two efforts to support CDOT in the area of Safety Performance Function (SPF) development. The first involved the data collection and development of SPFs for five categories of ramp terminals at diamond interchanges. For each category, data for the period 2000 to 2006 were collected at sites selected to ensure statewide geographical representation and coverage of the range of traffic volume and other variables in each category. The second effort involved estimating the overdispersion parameters for a number of existing SPFs already in use by CDOT for various roadway segment categories. These parameters are required for implementing the state-of-the-art empirical Bayes procedure for various safety management processes. The development of SPFs for the five categories of ramp terminals was successful. Separate SPFs were developed for total and for injury (fatal+injury) accidents. The calibration of overdispersion parameters for the existing roadway segment SPFs was also successful.

Implementation

The developed safety performance functions, as well as the estimated overdispersion parameters, can be used immediately by CDOT for applying state-of-the-art methodologies for road safety management activities.

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EXECUTIVE SUMMARY

CDOT's research and safety engineers are in the forefront of national efforts to develop methods that use Safety Performance Functions (SPFs) to screen large networks to find sites with a potential for safety improvement. CDOT has previously developed SPFs to identify freeway, rural roadway segments, and ten categories of intersections that have the potential for accident reduction. This report documents two further efforts to support CDOT in the area of SPF development.

The first effort involved the data collection and development of SPFs for ramp terminals at diamond interchanges. Five ramp terminal categories that are of highest priority for CDOT, and with sufficient samples for developing robust models, were included, as follows:

1. Stop-Controlled with two lanes on crossroad
2. Stop-Controlled with four lanes on crossroad
3. Signalized with two lanes on crossroad
4. Signalized with four lanes on crossroad
5. Signalized with six lanes on crossroad

For each category, data were collected at sites selected to ensure statewide geographical representation and coverage of the range of traffic volume and other variables in each category. Data were collected for the period 2000 to 2006.

The second effort involved estimating the overdispersion parameters for a number of existing SPFs already in use by CDOT for various roadway segment categories. These parameters, which are required for implementing the state-of-the-art empirical Bayes procedure for various safety management processes, could not be developed in the neural network modeling process used by CDOT to estimate the roadway segment SPFs.

The development of SPFs for the five categories of ramp terminals was successful. Separate SPFs were developed for total and for injury (fatal+injury) accidents. These SPFs compare favorably to those developed for another North American highway agency. The calibration of overdispersion parameters for the existing neural network SPFs was also successful.

It is recommended that data for additional sites be collected as they may become available. Additionally, as more years of crash and traffic data become available these data too can be

added to the database in order to continually add up-to-date information. The SPFs can be recalibrated to apply to these additional years of data using a procedure documented in the report. When several additional years of data are available, it may be desirable to calibrate a new set of original SPFs.

Implementation Statement

The developed safety performance functions can be used immediately by CDOT for applying state-of-the-art methodologies for road safety management activities, including screening the network to identify diamond interchange ramp terminals with a potential for safety improvement, diagnosing safety issues at specific ramp terminals, and evaluating the safety effectiveness of implemented countermeasures. The overdispersion parameters developed for roadway segments will facilitate the application of the empirical Bayes methodology for safety management activities for these site types.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Road safety management activities include screening the network for sites with a potential for safety improvement (network screening), diagnosing safety problems at specific sites, and evaluating the safety effectiveness of implemented countermeasures. It is important that these activities be both efficient and methodologically sound since resources would otherwise be wasted on unnecessary treatments for safe elements and elements deserving of treatment would be left untreated.

The state-of-the-art methodologies for conducting these activities make use of statistical models to predict expected accident frequencies using traffic volumes and other site characteristics as the input to the models (known as Safety Performance Functions or SPFs). The following is an example of an SPF for an intersection:

$$\text{Accidents/year} = (\text{alpha})\cdot(\text{AADTmaj})^{b1}\cdot(\text{AADTmin})^{b2}$$

Where,

- alpha, b1 and b2 are parameters estimated in the modeling process;
- AADTmaj and AADTmin are the estimated average annual daily traffic volumes on the major and minor roads, respectively.

CDOT’s research and safety engineers are in the forefront of national efforts to develop methods using SPFs to screen large networks to find sites with a potential for safety improvement. CDOT has previously developed SPFs to identify freeway, rural roadway segments, and ten categories of intersections that have the potential for accident reduction.

This report documents two efforts to support CDOT in the area of SPF development.

The first effort involves the data collection, modeling efforts, and findings of a research project to develop SPFs for ramp terminals at diamond interchanges. It was not feasible to collect data for all such ramp terminals under CDOT’s jurisdiction due to budget constraints. The sites pursued for this project were determined after considering the total number of locations in each category and the availability of existing minor road traffic counts. Staff from CDOT was also consulted to ensure that intersection categories that are of higher priority for CDOT were included. Following this evaluation, the analysis team developed a plan to select a random sample of sites for further data collection, keeping in mind that locations throughout Colorado geographically must be represented as well as a range of traffic volumes and other variables. Without such a diverse representation, the SPFs would not be applicable across the state and for the spectrum of pertinent variables.

Data were collected for five categories of ramp terminals at diamond interchanges using information from CDOT maintained roadways. SPFs were developed separately for Total and Injury (fatal+injury) accidents where possible. These five categories include:

6. Stop-Controlled with two lanes on crossroad
7. Stop-Controlled with four lanes on crossroad
8. Signalized with two lanes on crossroad
9. Signalized with four lanes on crossroad
10. Signalized with six lanes on crossroad

The second effort involved estimating the overdispersion parameters for a number of existing SPFs already in use by CDOT for roadway categories shown in **Table A**. The maximum likelihood procedure outlined in Section 6.1 was applied for this task. These SPFs were developed using a neural network modeling process that does not estimate an overdispersion parameters. Overdispersion estimates are, however, required in implementing the empirical Bayes procedure for various safety management processes. The output of the neural network modeling is a table giving the estimated number of accidents for a given AADT. The files provided by CDOT included predictions in increments of 50. The predictions were available for both total and fatal+injury crashes.

Table A. Neural Network Model Categories

Category	Description
rfrr2uh	Rural Flat and Rural Rolling Two-Lane Undivided Highways
rfrr4df	Rural Flat and Rural Rolling Four-Lane Divided Freeways
rfrr4dh	Rural Flat and Rural Rolling Four-Lane Divided Highways
rm2uh	Rural Mountainous Two-Lane Undivided Highways
rm4df	Rural Mountainous Four-Lane Divided Freeways
rm4dh	Rural Mountainous Four-Lane Divided Highways
ufur4df	Urban Flat and Urban Rolling Four-Lane Divided Freeways
ufur6df	Urban Flat and Urban Rolling Six-Lane Divided Freeways
ufur8df	Urban Flat and Urban Rolling Eight-Lane Divided Freeways

2.0 DATA ASSEMBLY

The data collection phase of the project involved two tasks: 1) compiling the existing ramp and cross street AADT data and accident data over the 2000 to 2006 study period into a consistent format and 2) collecting the remaining ramp and cross street ADT data.

For the recalibration of existing neural network SPFs, files were provided for each SPF type including each site, the traffic volumes, and the observed and predicted crash rates.

The accident data were provided by CDOT's Safety Engineering and Analysis group, which maintains a comprehensive set of databases containing detailed accident history as well as geometric data. The intersections were initially identified using the Colorado Roadway Information System (CORIS) database, which contains point location descriptions, number of travel lanes, and other pertinent details. The intersections were sorted into the appropriate categories and reviewed to ensure the CORIS data matched the in-situ intersection geometry. The resulting lists were used to extract and compile the accident history for each intersection.

Existing ramp and cross street AADT data were acquired from several different sources. If the cross street is a state highway, CDOT's DTD DataAccess Traffic Count Database provided 2010 daily counts at most interchange locations. Also, various traffic studies along the study corridors including, but not limited to, the North I-25 DEIS, I-70 PEIS, and the US-36 FEIS were revised and daily and peak hour traffic counts at cross streets and on-off-ramps were acquired. Of note, the peak hour counts from the various studies were adjusted to AADTs using peak to daily ratios. Finally, individual municipality (cities, counties, agency) count databases were reviewed and traffic counts at cross streets, ramp terminal intersections, and on / off-ramp were obtained.

These data were then supplemented with traffic counts completed in the field by All Traffic Data Services, Inc. Ramp and cross street ADT data were generally only available for one year, most frequently the year 2010. Because most traffic counts were outside of the study period for the crash data, these volumes were factored back to the 2000 to 2006 time period. Mainline freeway AADTs at the interchange locations were acquired from the year 2000 to 2010. To smooth out these AADTs, and to accommodate locations with missing AADTs in some years, the data for each site was fit to a simple linear regression model and the average AADT for each site determined. Next, the ratio of the AADT in each year to the average AADT was determined. These factors were then applied to the measured AADTs at the ramp terminal intersections to adjust the measured counts to an average AADT for the 2000 to 2006 study period.

The construction history at each location was determined and if any major construction occurred during the study period the data prior to this work were not included in the analysis.

Resource constraints prohibited collecting data for all locations in Colorado. Thus, data for a subsample were collected. To avoid biasing the developed models in the site selection process, the analysis team selected a random sample of sites for further data collection, keeping in mind that geographic regions throughout Colorado must be represented as well as a range of traffic volumes. Without such a diverse representation, the SPFs developed would not be applicable across the state and across the range of traffic volumes. The number of sites in the sample was determined considering both the cost of data collection and the analysis costs.

Table B summarizes the total number of sites, those with existing traffic counts and the total number of sites ultimately used for this study.

Table B. Summary of Data Collection

Full Description	Total Number of Sites	Sites with Existing Traffic Counts	Sites for Analysis	Total Crashes
Stop-controlled two-lanes on cross street	240	24	100	296
Stop-controlled four-lanes on cross street	14	2	14	139
Signalized two-lanes on cross street	23	10	22	315
Signalized four-lanes on cross street	138	36	84	5,751
Signalized six-lanes on cross street	24	8	20	2,470

Table C provides summary statistics for the average yearly accident frequencies and average ramp and crossroad AADTs for the sites used in developing the SPFs. Data plots of total and fatal+injury crash counts per year versus AADT are provided for all five categories in **Appendix A.**

Table C. Summary Statistics of Data

Full Description	Average Crossroad AADT			Average On Ramp AADT			Average Off Ramp AADT			Total Accidents/Year			Fatal+Injury Accidents/Year		
	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean
Stop-controlled two-lanes on cross street	24	14,600	4,311	33	9,259	1,623	43	8,713	1,547	0.00	4.00	0.44	0.00	1.43	0.12
Stop-controlled four-lanes on cross street	3,539	17,062	9,290	653	9,180	2,885	543	8,522	2,730	0.00	9.29	1.44	0.00	3.14	0.41
Signalized two-lanes on cross street	3,626	19,139	12,651	701	7,416	3,546	801	24,343	4,942	0.00	6.57	2.05	0.00	2.14	0.44
Signalized four-lanes on cross street	6,468	52,999	27,229	268	19,490	7,579	268	17,438	7,173	0.00	37.43	10.07	0.00	13.71	2.66
Signalized six-lanes on cross street	35,031	66,384	46,696	4,384	22,668	10,946	678	23,435	10,564	0.50	43.0	19.64	0.00	8.71	4.50

3.0 STUDY METHODOLOGY

Consistent with state-of-the-art methods, generalized linear modeling, with the specification of a negative binomial (NB) error structure, was used to develop the SPFs. In turn, the specification of an NB error structure allows for the direct estimation of the overdispersion parameter since this is a parameter of the NB distribution. As noted earlier, this parameter is used in the empirical Bayes procedure for estimating the expected safety performance of an intersection for various safety management purposes (e.g., those envisaged in *SafetyAnalyst*[1]).

SPFs were developed separately for total and injury (fatal+injury) accidents where possible. In developing the SPFs, alternative model forms were investigated using the integrate-differentiate (ID) method documented by Hauer[2]. Briefly, this method involves plotting the cumulative products of the crash count and the value of the independent variable of interest against the variable of interest. While it is typically difficult to observe patterns on simple plots of crash frequency against an independent variable (such as traffic volume), this cumulative plot makes such patterns much easier to spot. The relationship between crash frequency and the variable of interest is then the derivative of this observed relationship.

Alternative models were compared using other standard measures of goodness-of-fit such as the mean residuals (observed minus predicted) and the value of the overdispersion parameter which is estimated as part of the modeling process and is in itself a reliable goodness-of-fit measure, with a smaller overdispersion parameter indicating a model that better captures the overdispersion in the data.

It is important to not only evaluate a model based on overall measures but also to evaluate how it performs over the range of covariates. This evaluation makes use of cumulative residual (CURE) plots. In the CURE method, documented by Hauer & Bamfo[2], the cumulative residuals (the difference between the observed and predicted values for each site) are plotted in increasing order for each covariate separately. Also plotted are graphs of the 95% confidence limits. If there is no bias in the model, the plot of cumulative residuals should oscillate around the x-axis

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1 http://www.safetyanalyst.org/

2 Hauer, E. and J. Bamfo, "Two Tools for Finding What Function Links the Dependent Variable to the Explanatory Variables". Available at www.roadsafetyresearch.com.

without systematic over or under-prediction, and stay inside of these confidence limits. The graph shows how well the model fits the data with respect to each individual covariate. **Figure 1** illustrates a CURE plot for one model for the major road AADT covariate. The indication is that the fit is very good for this covariate in that the cumulative residuals oscillate around the value of zero and lie between the two standard deviation boundaries.

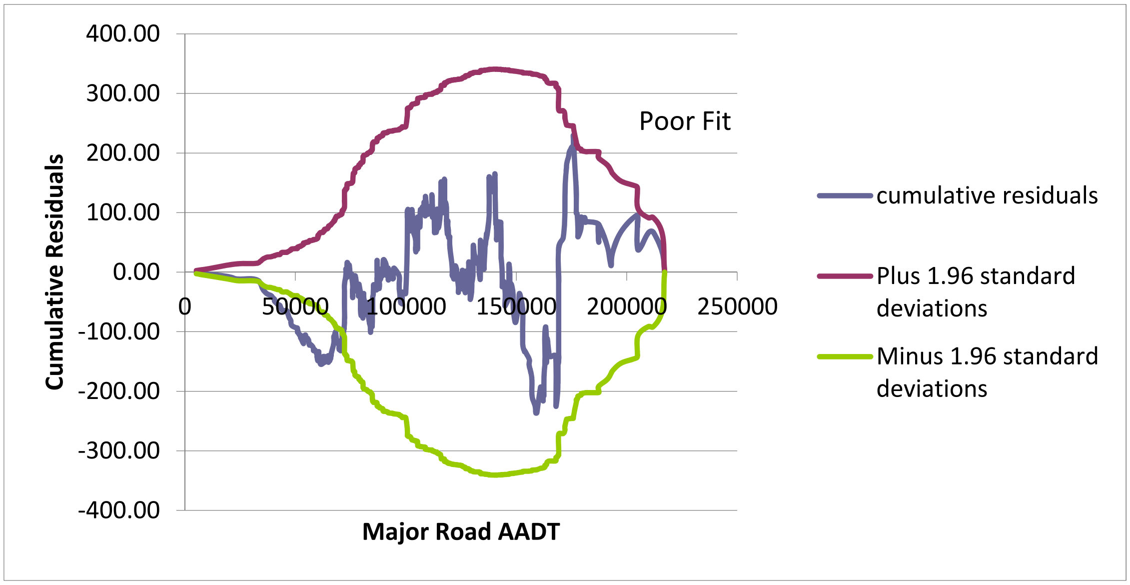


Figure 1. Example of CURE Plot

4.0 SPFS CALIBRATED

Models were successfully developed for each of the five intersection categories. For types 1 and 4, the sample sizes permitted those intersection types to be modeled on their own. For type 2, only 14 locations existed in the database, which is an insufficient size for modeling. To develop a model for type 2 sites these intersections were therefore combined with type 1, creating a group of all stop-controlled intersections. Similarly, type 3 (22 sites) and type 5 (20 sites) were combined with type 4, creating a group of all signalized intersections. In each case, a factor variable identifying the intersection type was included to account for the differing number of lanes on the crossroad. Note that the overdispersion in these cases was estimated separately for each group by a maximum likelihood program that does not provide the standard errors. These new models do not replace the models for types 1 and 4, which were estimated exclusively on their own.

The available independent variables, in addition to the intersection type, which reflects the type of traffic control (signalized versus stop-controlled) and the number of lanes on the crossroad, include the AADT on the crossroad, the off-ramp and the on-ramp. Note that the on-ramp traffic volumes would include vehicles already counted on the crossroad and which were traveling onto the freeway mainline. Exploration of unconventional model forms was not particularly successful although this was not surprising given the relatively small sample sizes available. On-ramp AADT, included as a variable on its own, or as a proportion of the crossroad AADT, was not statistically significant although the effect was as expected in that an increase in the volume is associated with an increase in crash frequency. That on-ramp AADT was not statistically significant is not particularly surprising given that its value includes volumes already counted on the crossroad, resulting in a direct correlation between these two variables.

The final model form for all intersection categories is as follows:

$$Crashes/Year = \alpha(CrossRoadAADT)^{b}(OfframpAADT)^{c}$$

where,
CrossRoadAADT is the AADT on the crossroad
OffRampAADT is the AADT on the Off-ramp
α,b,c are the model parameters to be estimated

This is the same model form used in the Interchange Safety Analysis Tool[3] for ramp terminals.

Table D provides the SPFs developed for total crashes. The standard errors of the estimated parameters indicate that they are generally highly significant. The properties of the standard errors are such that an estimated parameter is within the range of the estimated value plus or minus 1.64 standard errors with 90 percent confidence. If this range does not include the value of zero, then the parameter is significant at the 90 percent level. As an example, for the Category 1 model in **Table C**, the parameter β1 is estimated as 0.5714 with a standard error of 0.1626. Thus the 90% confidence interval of the estimated parameter is 0.3047 to 0.8381. Because this range does not include the value 0, it can be stated that the estimated parameter is statistically significant at the 90% level. The overdispersion parameters also indicate that the models provide a reasonable fit to the data. Note that the properties of the overdispersion parameter are such that smaller values indicate a stronger fit to the data. Although there are not rules as to how small the overdispersion parameter should be to be considered acceptable, experience indicated that values of approximately one or less are quite satisfactory.

Table D. Summary of Total Crash Models

Category	Full Description	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	Over-dispersion Parameter (s.e.)
1	Stop-controlled two-lanes on cross street	-9.7459 (1.2954)	0.5714 (0.1626)	0.5699 (0.1877)	1.2192 (0.2758)
2	Stop-controlled four-lanes on cross street	-10.0066 (1.3994)	0.6148 (0.1580)	0.5797 (0.1720)	0.9659 (n/a)
3	Signalized two-lanes on cross street	-10.2230 (1.8806)	0.9238 (0.1816)	0.2653 (0.1048)	0.4031 (n/a)
4	Signalized four-lanes on cross street	-9.7124 (2.0222)	0.8644 (0.2086)	0.3614 (0.1288)	0.6020 (0.0961)
5	Signalized six-lanes on cross street	-9.3145 (1.8517)	0.9238 (0.1816)	0.2653 (0.1048)	0.5912 (n/a)

Table E provides the SPFs developed for fatal+injury crashes. As was the case for the total crash SPFs, the magnitude of the estimated parameters are in line with models calibrated for other jurisdictions, and the standard errors of the estimated parameters indicate that they are generally highly significant. The overdispersion parameters also indicate that the models provide a reasonable fit to the data.

[3] Torbic, D. Harwood, D., Gilmore, D. and K. Richard. Interchange Safety Analysis Tool (ISAT): User Manual. FHWA-HRT-07-045. http://www.tfhrc.gov/safety/pubs/07045/07045.pdf

Table E. Summary of Fatal+Injury Crash Models

Category	Full Description	ln(α) (s.e.)	β1 (s.e.)	β2 (s.e.)	Over-dispersion Parameter (s.e.)
1	Stop-controlled two-lanes on cross street	-10.2946 (1.6542)	0.7147 (0.2141)	0.3019 (0.2147)	0.8408 (0.3827)
2	Stop-controlled four-lanes on cross street	-10.9992 (1.8300)	0.7652 (0.2165)	0.3749 (0.2032)	1.1610 (n/a)
3	Signalized two-lanes on cross street	-10.5153 (2.0092)	0.7465 (0.1929)	0.3195 (0.1116)	0.4862 (n/a)
4	Signalized four-lanes on cross street	-10.6967 (2.1105)	0.8088 (0.2182)	0.3871 (0.1362)	0.6099 (0.1102)
5	Signalized six-lanes on cross street	-9.3508 (1.9765)	0.7465 (0.1929)	0.3195 (0.1116)	0.5682 (n/a)

CURE plots for the SPFs for both the crossroad and off-ramp AADT are provided for all five categories in **Appendix B**. The CURE plots further indicate that the models are generally fitting the data well since the plotted lines are largely within the two standard error boundaries. When the cumulative residuals do stray outside these limits, the magnitude of the cumulative residuals compared to the total number of crashes is relatively small, approximately ten percent of the total number of crashes within the group.

Alternate model forms were attempted with the aim of improving the model performance in those ranges of crossroad or off-ramp AADT where the models are showing bias. One of these attempts included allowing the estimated parameters for the AADT variables to vary by intersection type for those types that were grouped together for modeling. Another attempt was introduction of the Hoerl's function into the model, which allows an inflection point in the relationship between accidents and the AADT variables. However, these attempts were not successful. Given the relatively low number of crashes in most groups, more complex model forms are difficult to calibrate with statistical significance.

In **Appendix C**, the various models are plotted against each other for the crossroad AADT data range using off-ramp AADTs of 2,000 for unsignalized intersections and 7,500 for signalized intersections. Also shown on these plots are the comparable models from the Interchange Safety Analysis Tool (ISAT)[3]. These plots aid in arriving at conclusions regarding the relative safety of various intersection types given similar traffic volumes.

Appendix D provides for comparison, the ramp terminal models calibrated recently for Ontario freeways. For Colorado, it was feasible to develop more detailed models, in that there are up to three categories of models for number of lanes on the crossroad and, for stop-controlled intersections, it was possible to estimate separate coefficients for crossroad and ramp AADTs. The FI models are the most comparable ones and these indicate that the Colorado models are not inconsistent. For example, for Ontario, the coefficient for total entering AADT for stop-controlled intersections is 0.5028, which is bracketed nicely by the crossroad and ramp AADT coefficients for Colorado. And for signalized intersections, for both Ontario and Colorado FI models, the coefficients suggest a stronger influence for crossroad AADT than for ramp AADT.

5.0 CALIBRATED OVERDISPERSION PARAMETERS FOR NEURAL NETWORK MODELS

Overdispersion parameters were estimated for all the neural network models using the maximum likelihood procedure described in Section 6.1 and are shown in **Table F**. CDOT provided the output of the neural network modeling, which is a table giving the estimated number of accidents for a given AADT. Some categories have very few sites so the results may appear very good because there is an overfitting of the data; these include:

- Rfrr4dh
- Rm4df
- Rm4dh
- Ufur8df

Table F. Summary of Overdispersion Parameters for Neural Network Models

Category	Crash Type	Overdispersion	No. Observations	No. Sites	Sum of Crashes
rfrr2uh	Total	0.461	4221	422	7,408
rfrr2uh	Injury	0.324	4221	422	2,686
rfrr4df	Total	0.116	789	79	11,004
rfrr4df	Injury	0.113	789	79	4,481
rfrr4dh	Total	0.404	80	8	460
rfrr4dh	Injury	0.681	80	8	204
rm2uh	Total	0.340	3034	303	13,060
rm2uh	Injury	0.389	3034	303	5,121
rm4df	Total	0.080	160	16	5,909
rm4df	Injury	0.013	160	16	1,850
rm4dh	Total	0.080	40	4	1,143
rm4dh	Injury	0.080	40	4	381
ufur4df	Total	0.206	770	77	19,886
ufur4df	Injury	0.205	770	77	6,687
ufur4dfnn	Total	0.207	770	77	19,886
ufur4dfnn	Injury	0.205	770	77	6,687
ufur6df	Total	0.119	341	34	21,225
ufur6df	Injury	0.097	341	34	5,856
ufur6dfnn	Total	0.119	341	34	21,225
ufur6dfnn	Injury	0.096	341	34	5,856
ufur8df	Total	0.161	84	8	11,796
ufur8df	Injury	0.120	84	8	3,021

6.0 RECALIBRATION PROCEDURE

The SPFs developed apply to similar ramp terminal intersections at diamond interchanges under CDOT jurisdiction during the time period for which the data were collected. It may be desirable at a future time period to recalibrate the models for data from future years. Expected accident frequencies may change over time due to issues such as changes to reporting practices, demographics, statewide safety programs, etc. The desirable recalibration sample size would be such that there are a minimum of 30 to 50 sites of the same site type and at least 100 observed accidents per year.

For the sample, data are collected to apply the SPFs to predict the number of accidents at each site. The ratio of the sums of observations to sum of predictions is used as an estimate of the calibration factor. This calibration factor is then added as a multiplier to the original SPF. This is essentially the same recalibration procedure documented in the Highway Safety Manual for applying an SPF to a different time period or jurisdiction.

It is also logical to recalibrate the overdispersion parameter as this not only indicates how well the recalibrated SPF is fitting the data but can also be used in the empirical Bayes methodology. Procedures with varying complexities for recalibrating the overdispersion parameter are provided below.

6.1 Estimation of overdispersion parameter (k) by maximum likelihood

The maximum likelihood method estimates the most likely value of the dispersion parameter and is the preferred approach as it is more accurate. The log-likelihood is calculated for a range of possible values of *k*, and the value of *k* with the largest log-likelihood is selected. If there is no such peak in the initial range selected, then a broader range of potential values of *k* is used. It is recommended to initially use values of *k* in increments of 0.5 to get a rough estimate and then to use increments of 0.05 to arrive at the final estimate of *k*.

For each of *j* = 1 to N sites, the following equations are applied:

a = (1/*k*)*LOG((1/*k*)/predicted);
b = ((1/k)+observed)*LOG((1/*k*)/predicted+1);

$$c = \sum_{i=1}^{observed} LOG((1/k) + i - 1)$$

Where,

k = the overdispersion parameter
predicted = the number of crashes predicted at site j by the recalibrated accident prediction model
observed = the crash frequency observed at site j

The log-likelihood for k is then calculated as:

$$Log - Likelihood = \sum_{j=1}^{N} a - \sum_{j=1}^{N} b + \sum_{j=1}^{N} c$$

Illustration - As an example, consider a fictitious dataset of sites including the following site j:

<u>Site *j*</u>
Observed crash frequency = 4
Predicted crash frequency = 4.5

Now consider that the analyst has selected a range of *k* from 0.50 to 0.95 in increments of 0.05. To illustrate the use of the above equations we will use the value of *k* = 0.40

a = (1/0.40)*LOG((1/0.40)/4.5) = 2.2447
b = ((1/0.40)+4)*LOG((1/0.40)/4.5+1) = 1.2473
c = LOG(1/0.40+1-1)+ LOG(1/0.40+2-1)+ LOG(1/0.40+3-1)+ LOG(1/0.40+4-1) = 2.3356

Similar calculations are then performed for each site and the log-likelihood calculated. For *k* = 0.40, the table below shows that the log-likelihood is estimated as 2705.

The log-likelihood is calculated for all possible values of *k* selected. As can be seen below, there is a peak value of the log-likelihood when *k* = 0.75 and the value of log-likelihood is 2718. Thus the estimated value of *k* is 0.75.

k	Log-Likelihood
0.40	2705
0.45	2707
0.50	2708
0.55	2711
0.60	2712
0.65	2714
0.70	2716
0.75	2718
0.80	2715
0.85	2713
0.90	2708
0.95	2706

6.2 Estimation of overdispersion parameter (k) by linear regression

Step 1: For each site, use the recalibrated accident prediction model to estimate the expected number of accidents (P). Also compute P^2.

Step 2: For each site, determine the value of the squared residual (SR):

$$SR = (P - Accident\ count)^2$$

Step 3: Subtract the value of P from the squared residual (SR). This gives an estimate of $P^2 * k$:

$$[\text{Estimate of } P^2 * k\ ] = SR - P$$

Step 4: Fit a linear model through the origin with $P^2 * k$ as the dependent variable and P^2 as the independent variable. An ordinary least squared regression procedure such as can be executed in MS EXCEL should suffice.

Step 5: The calibrated slope of the regression line is an estimate of k.

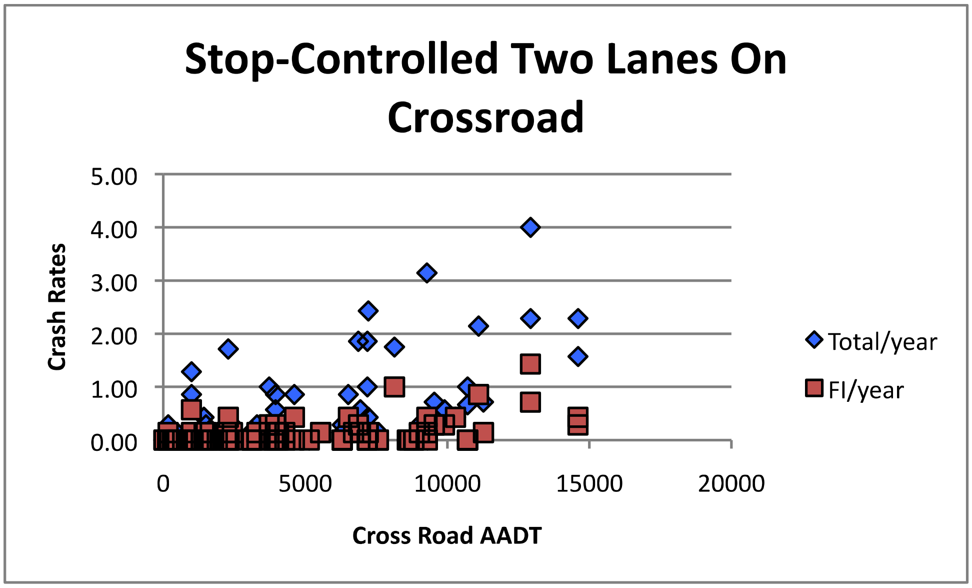
7.0 CONCLUSIONS AND RECOMMENDATIONS

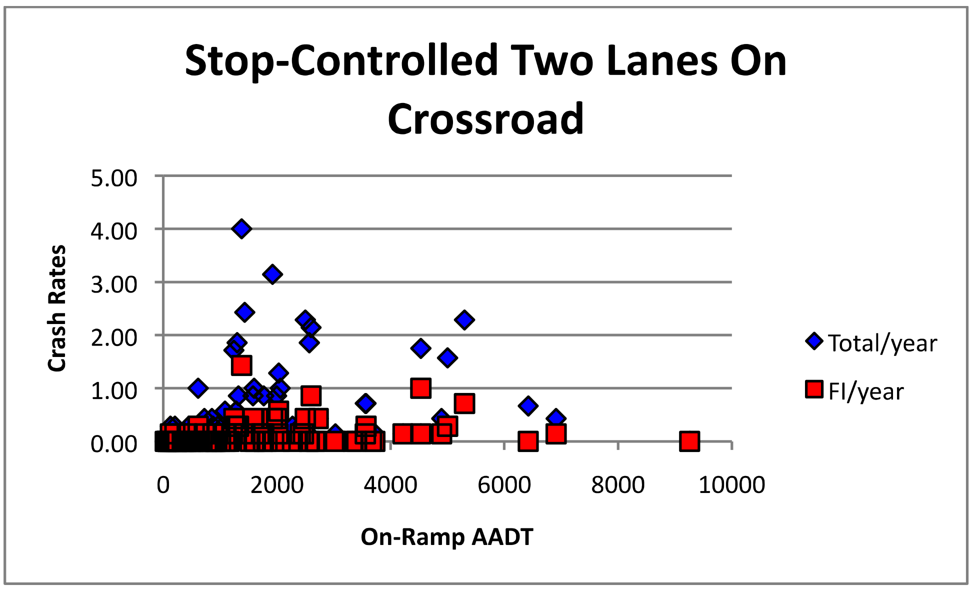
The development of SPFs for five categories of ramp terminals at diamond interchanges was successful. Separate models were developed for total and for injury (fatal+injury) accidents. Alternate model forms were attempted, including the Hoerl's function, which allows an inflection point in the relationship between accidents and the AADT variables. However, these attempts were not successful. Given the relatively low number of crashes in most groups more complex model forms are difficult to calibrate with statistical significance.

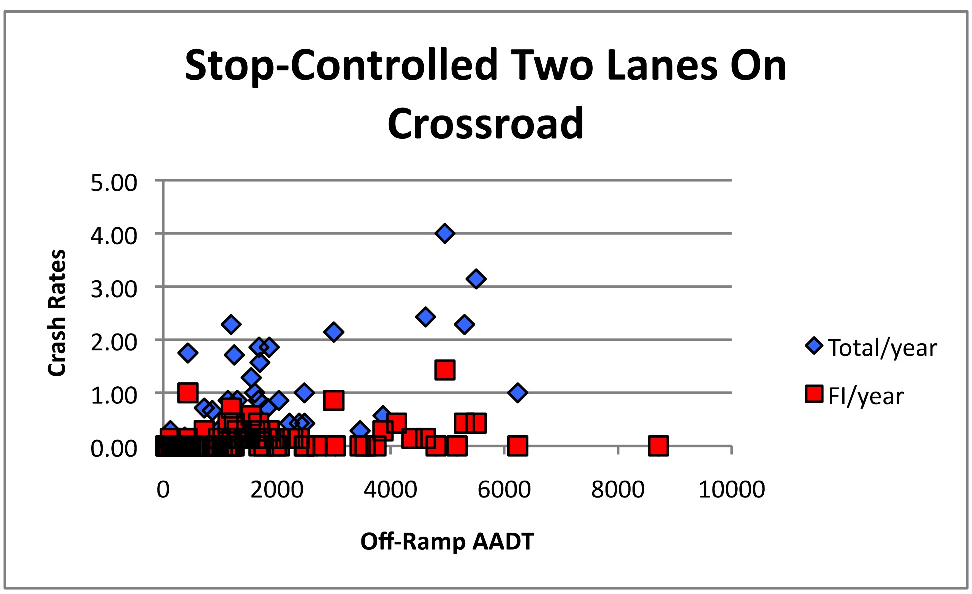
It is recommended that data for additional sites be collected as they may become available. Additionally, as more years of crash and traffic data become available these data too can be added to the dataset in order to continually add up-to-date information. The models can be recalibrated to apply to these additional years of data. When several additional years of data are available, it may be desirable to calibrate a new set of original SPFs.

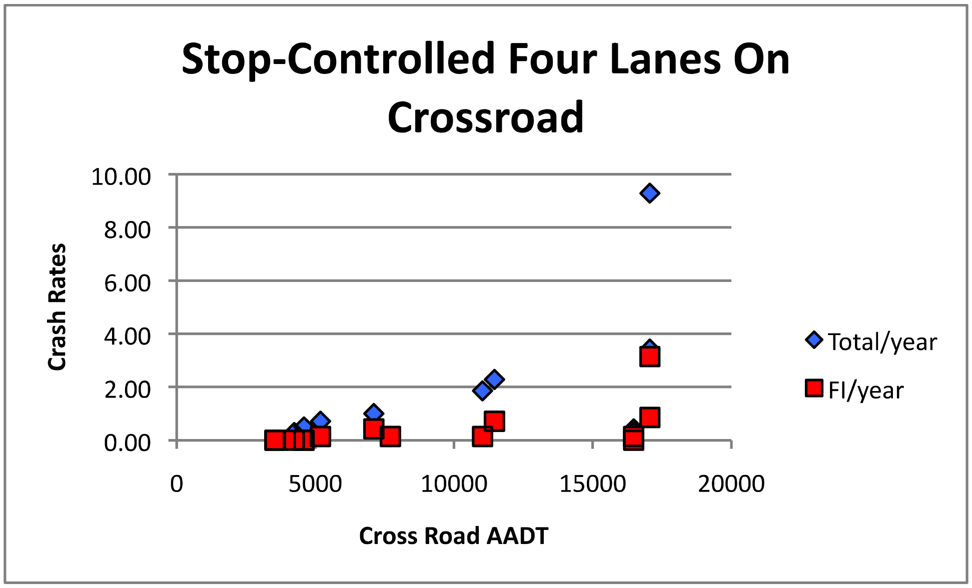
The calibration of overdispersion parameters for the existing neural network SPFs was also successful.

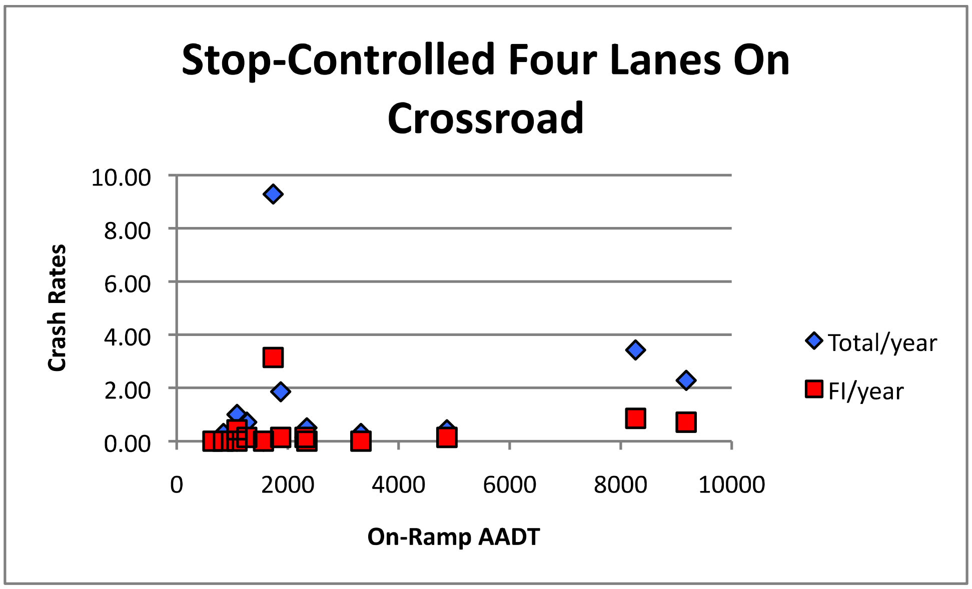
APPENDIX A: DATA PLOTS

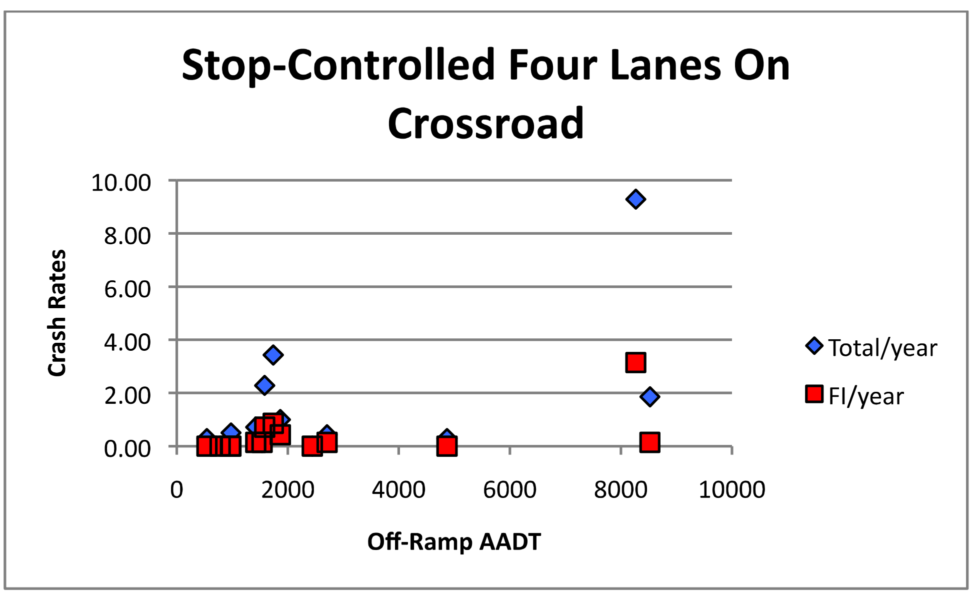


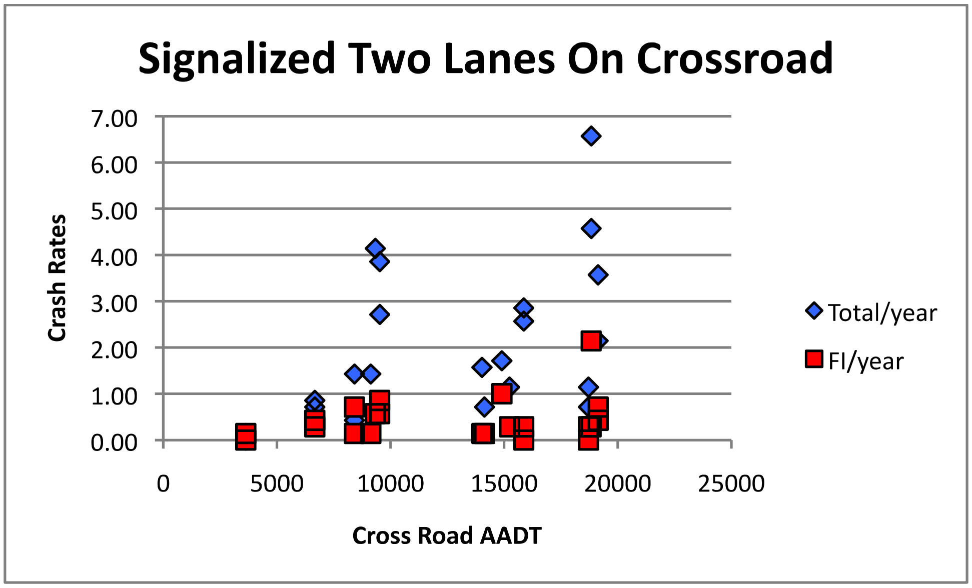


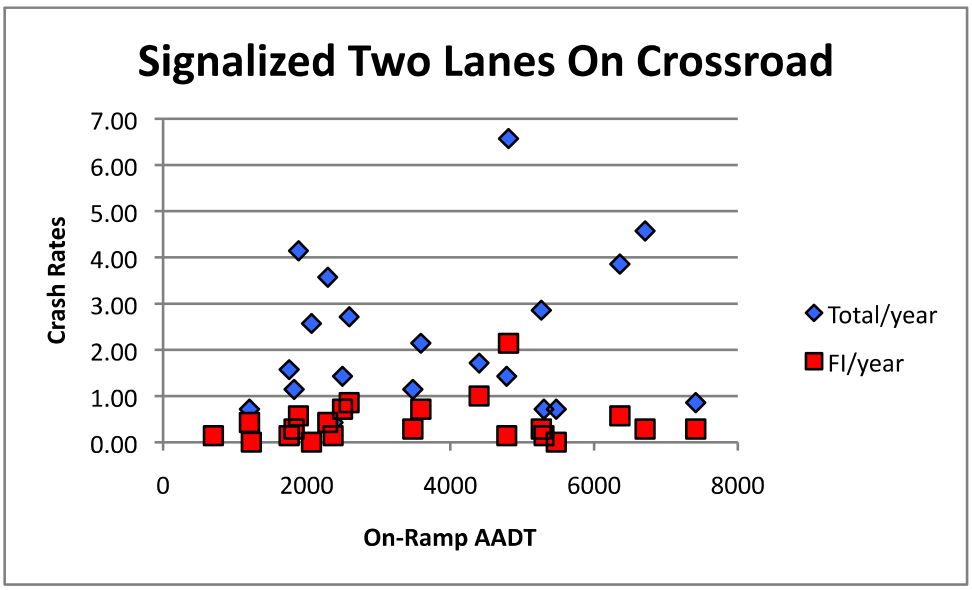


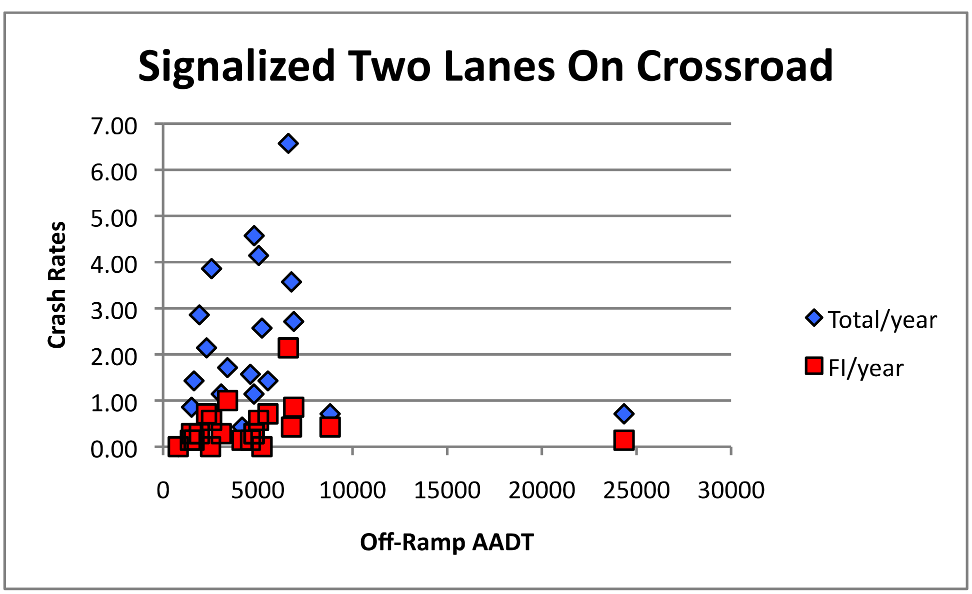

Stop-Controlled Four Lanes On Crossroad
Crash Rates
10.00
8.00
6.00
4.00
2.00
0.00
0
5000
10000
15000
20000
Cross Road AADT
Total/year
FI/year

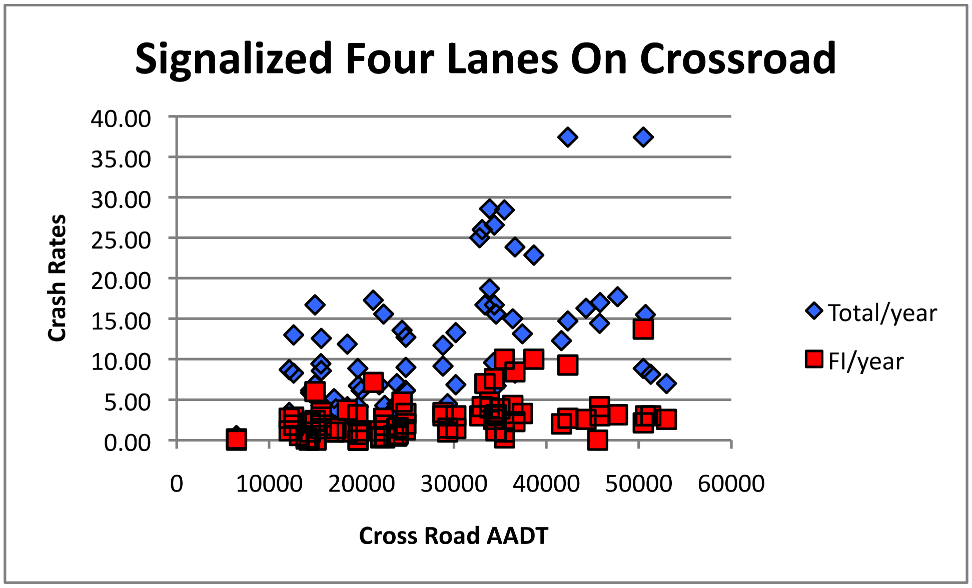

Stop-Controlled Four Lanes On Crossroad
Crash Rates
10.00
8.00
6.00
4.00
2.00
0.00
0
2000
4000
6000
8000
10000
On-Ramp AADT
Total/year
FI/year

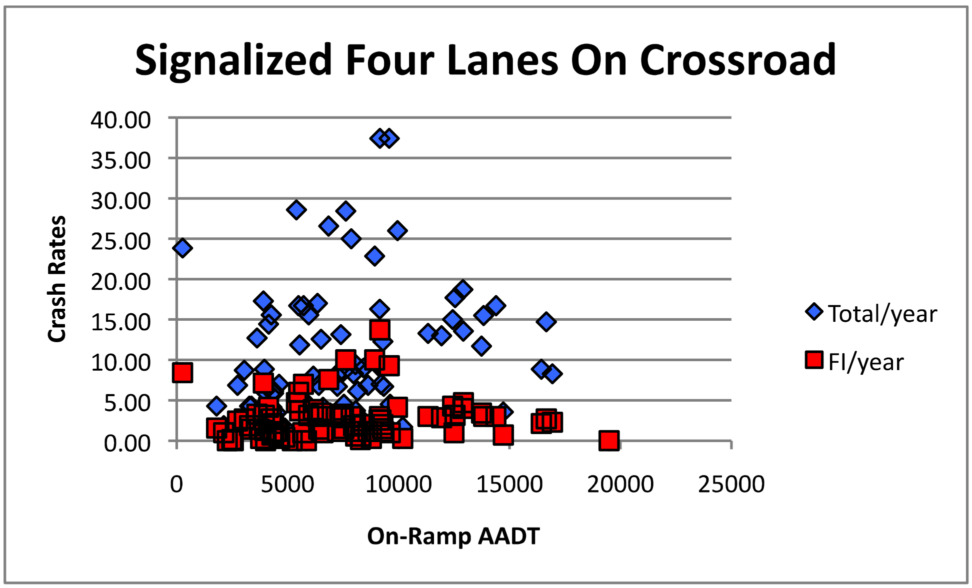

Stop-Controlled Four Lanes On Crossroad
Crash Rates
10.00
8.00
6.00
4.00
2.00
0.00
0
2000
4000
6000
8000
10000
Off-Ramp AADT
Total/year
FI/year


Signalized Two Lanes On Crossroad
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Crash Rates
0
5000
10000
15000
20000
25000
Cross Road AADT
Total/year
FI/year


Signalized Two Lanes On Crossroad
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Crash Rates
0
2000
4000
6000
8000
On-Ramp AADT
Total/year
FI/year


Signalized Two Lanes On Crossroad
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Crash Rates
0
5000
10000
15000
20000
25000
30000
Off-Ramp AADT
Total/year
FI/year


Signalized Four Lanes On Crossroad
Crash Rates
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
10000
20000
30000
40000
50000
60000
Cross Road AADT
Total/year
FI/year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Crash Rates
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35.00
30.00
25.00
20.00
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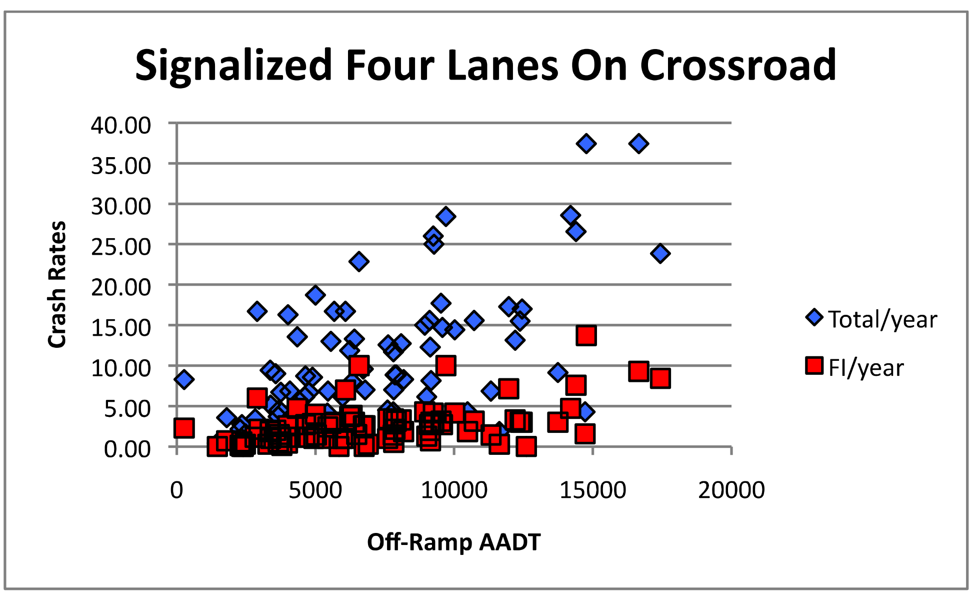
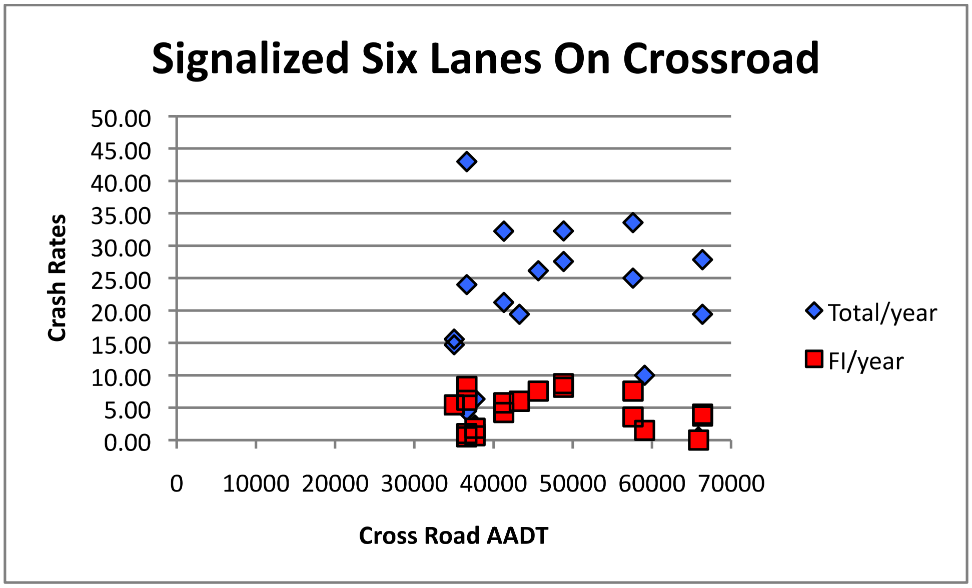
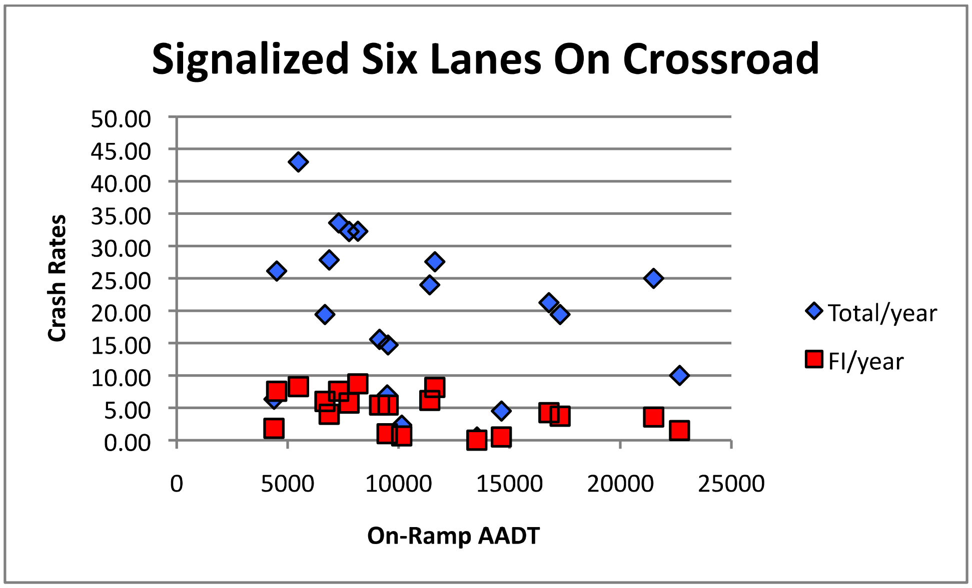
10.00
5.00
0.00
0
5000
10000
15000
20000
25000
On-Ramp AADT
Total/year
FI/year


Signalized Four Lanes On Crossroad
Crash Rates
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5000
10000
15000
20000
Off-Ramp AADT
Total/year
FI/year


Signalized Six Lanes On Crossroad
Crash Rates
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
10000
20000
30000
40000
50000
60000
70000
Cross Road AADT
Total/year
FI/year


Signalized Six Lanes On Crossroad
Crash Rates
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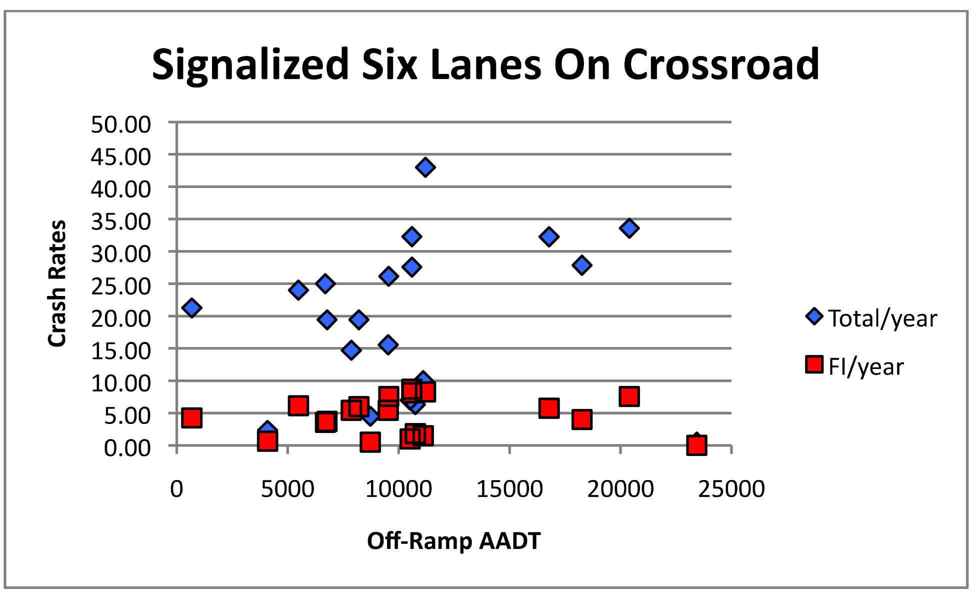
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5000
10000
15000
20000
25000
On-Ramp AADT
Total/year
FI/year


Signalized Six Lanes On Crossroad
Crash Rates
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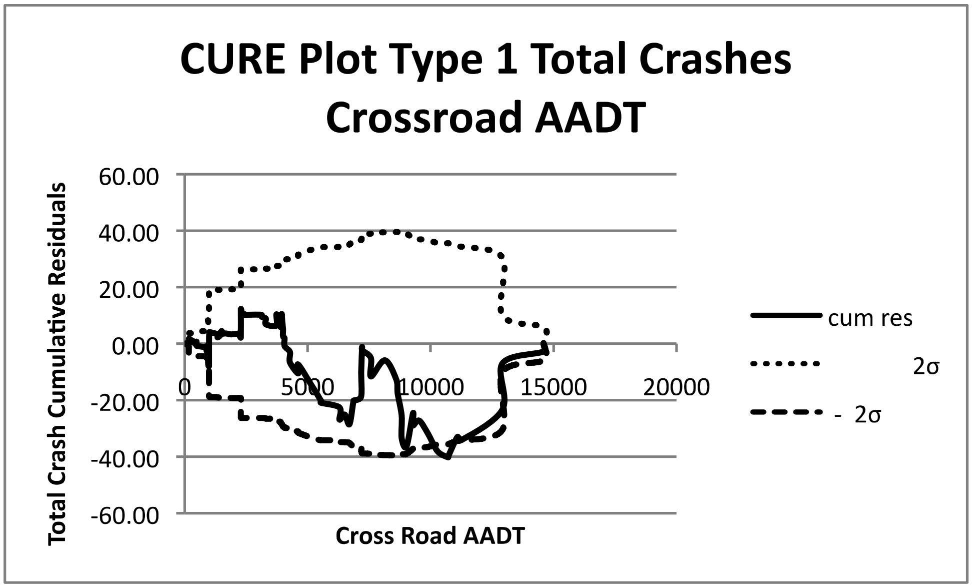
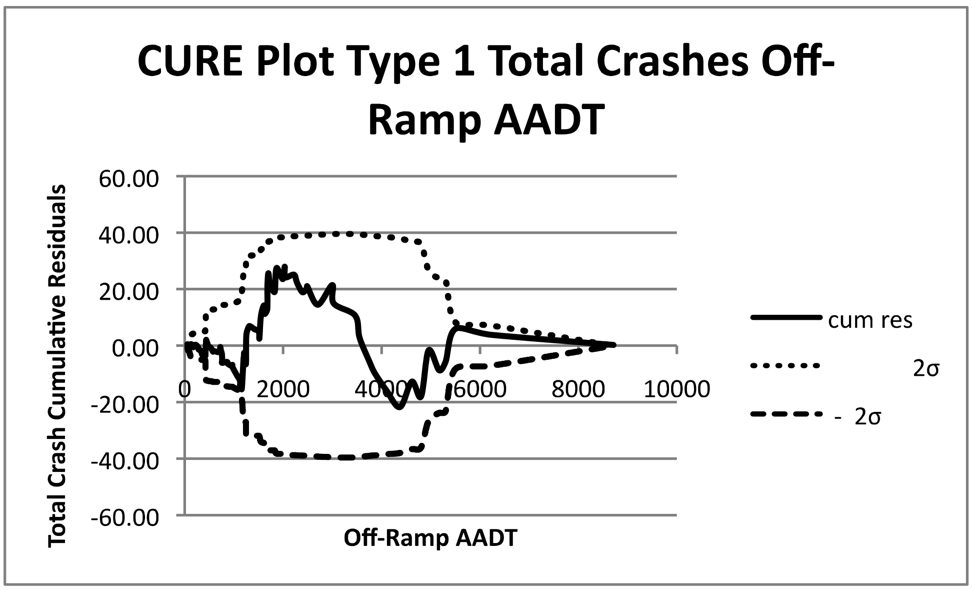
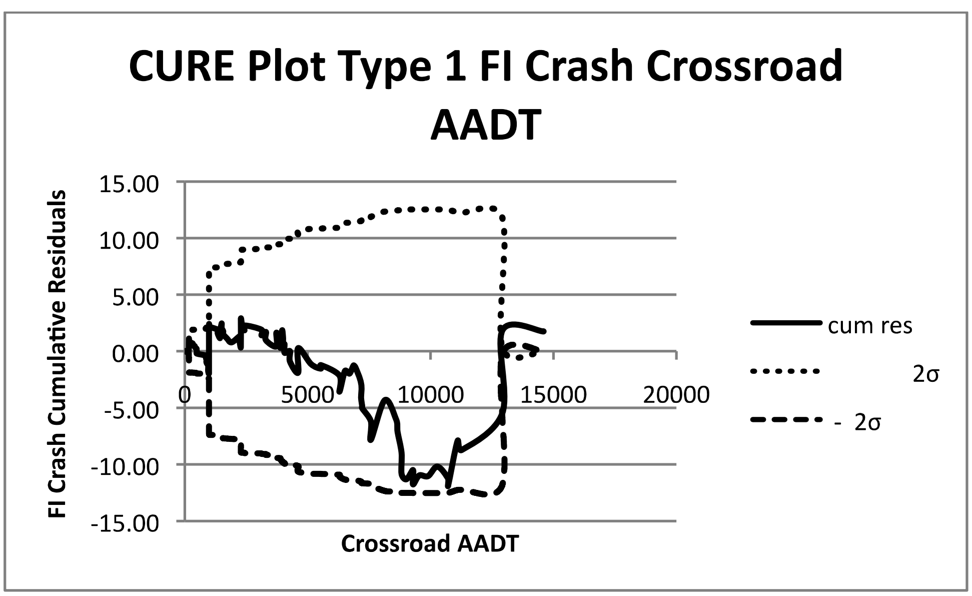
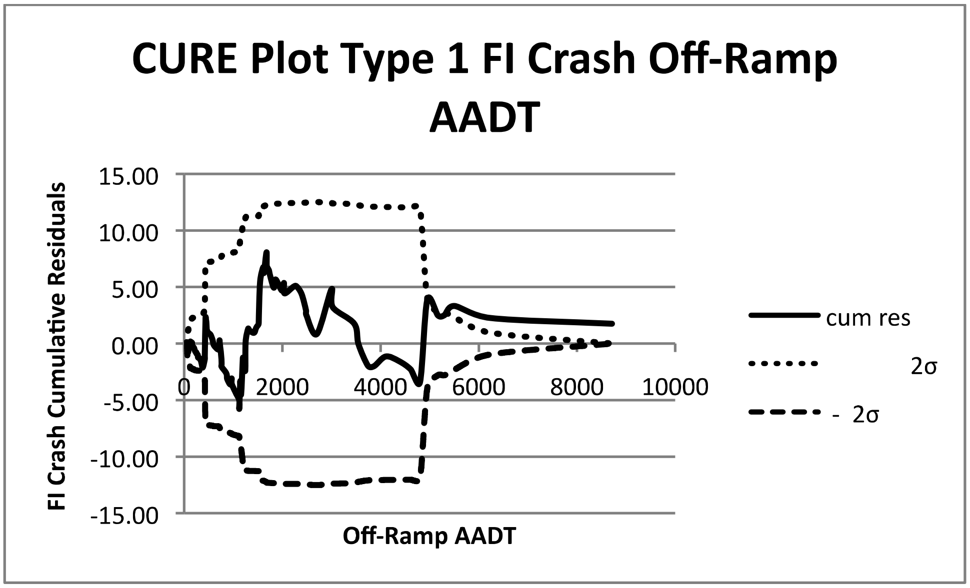
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5000
10000
15000
20000
25000
Off-Ramp AADT
Total/year
FI/year

APPENDIX B: CURE PLOTS





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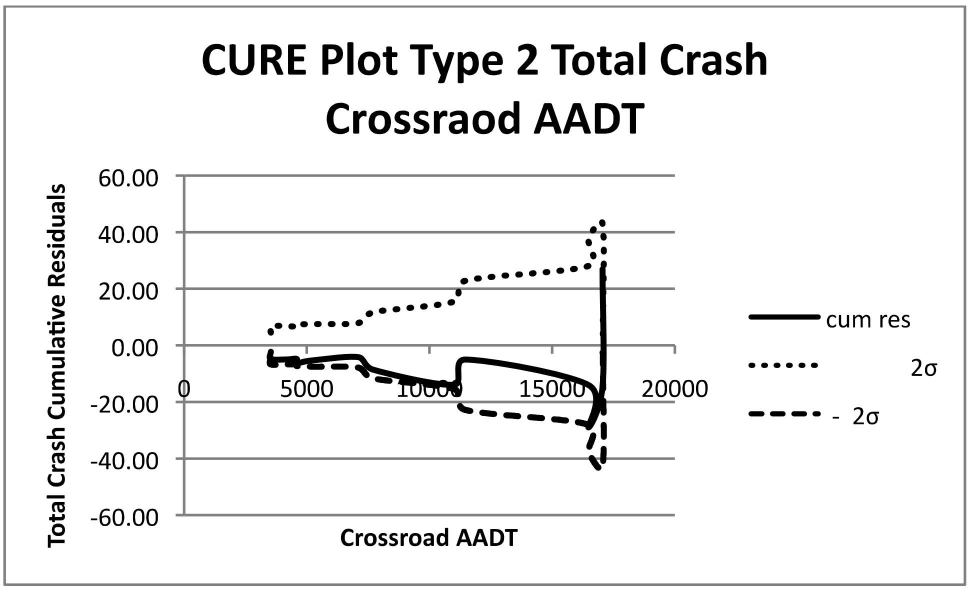
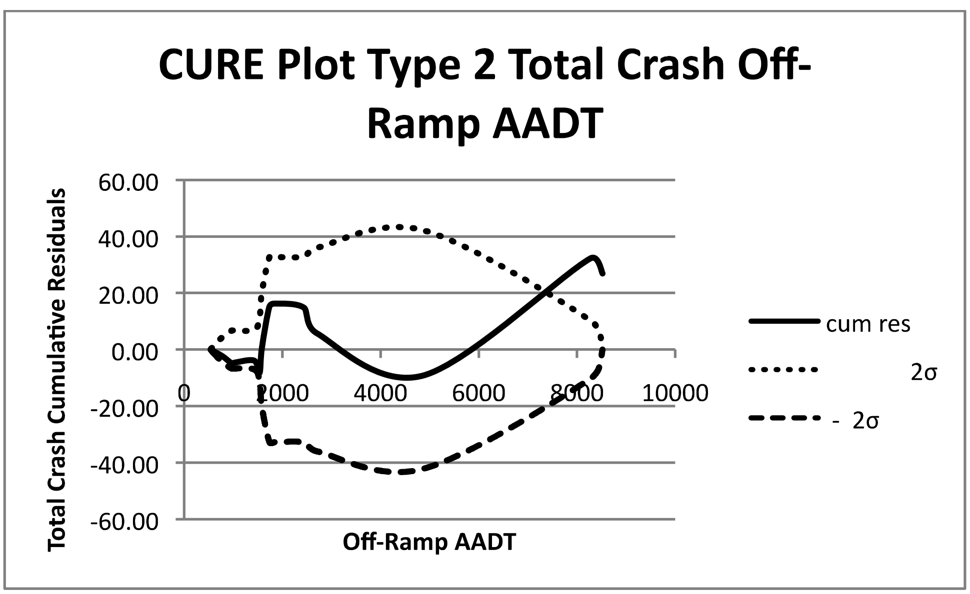
FI Crash Cumulative Residuals
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
0
2000
4000
6000
8000
10000
Off-Ramp AADT
cum res
2σ
- 2σ


CURE Plot Type 2 Total Crash Crossraod AADT
Total Crash Cumulative Residuals
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
0
5000
10000
15000
20000
Crossroad AADT
cum res
2σ
- 2σ


CURE Plot Type 2 Total Crash Off-Ramp AADT
Total Crash Cumulative Residuals
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40.00
20.00
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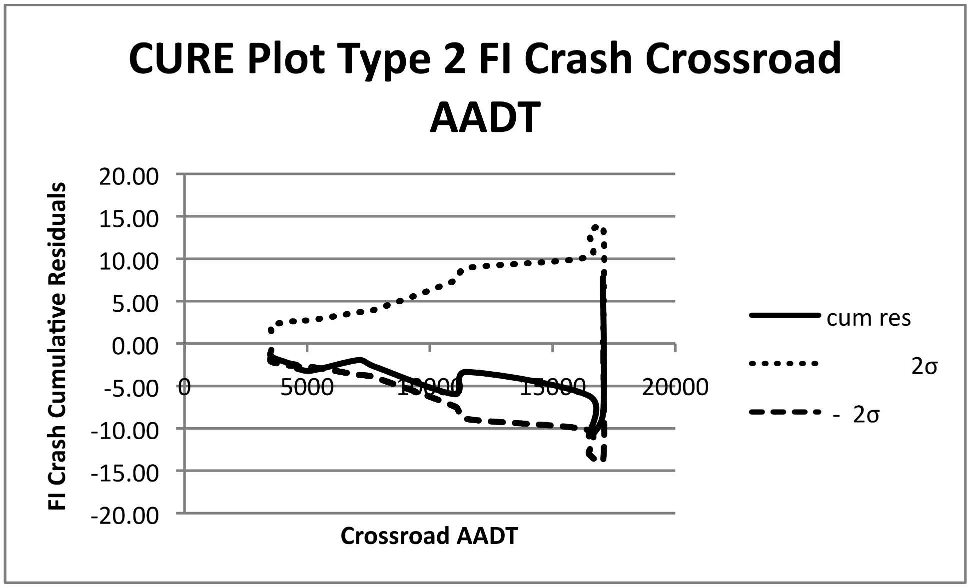
-40.00
-60.00
0
2000
4000
6000
8000
10000
Off-Ramp AADT
cum res
2σ
- 2σ


CURE Plot Type 2 FI Crash Crossroad AADT
FI Crash Cumulative Residuals
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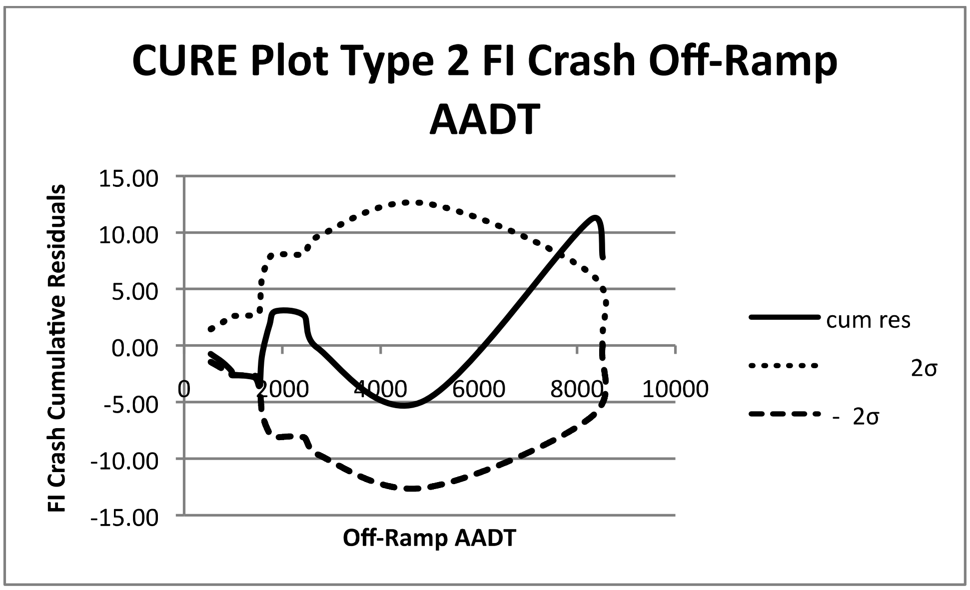
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
5000
10000
15000
20000
Crossroad AADT
cum res
2σ
- 2σ


CURE Plot Type 2 FI Crash Off-Ramp AADT
FI Crash Cumulative Residuals
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10.00
5.00
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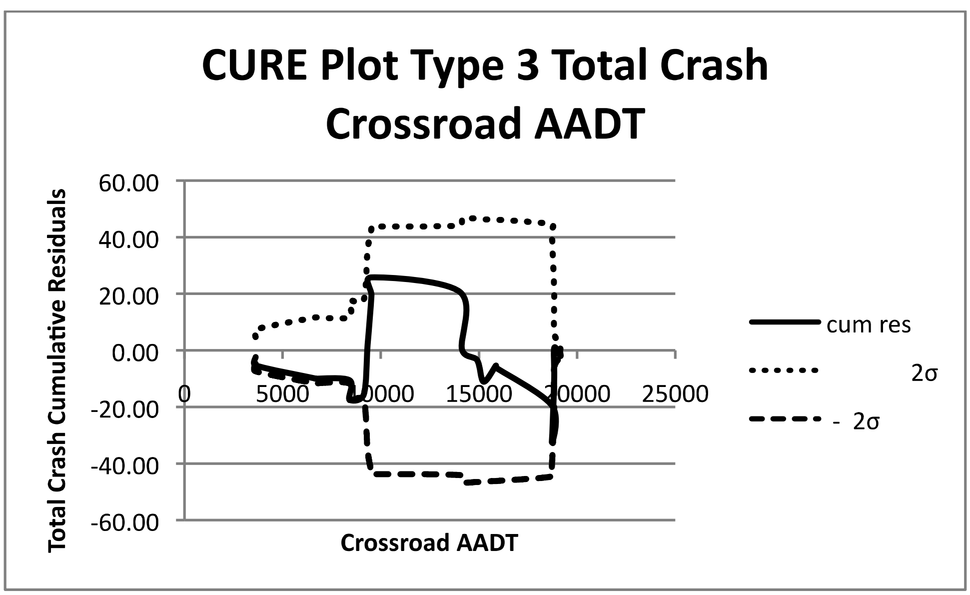
-10.00
-15.00
0
2000
4000
6000
8000
10000
Off-Ramp AADT
cum res
2σ
- 2σ


CURE Plot Type 3 Total Crash Crossroad AADT
Total Crash Cumulative Residuals
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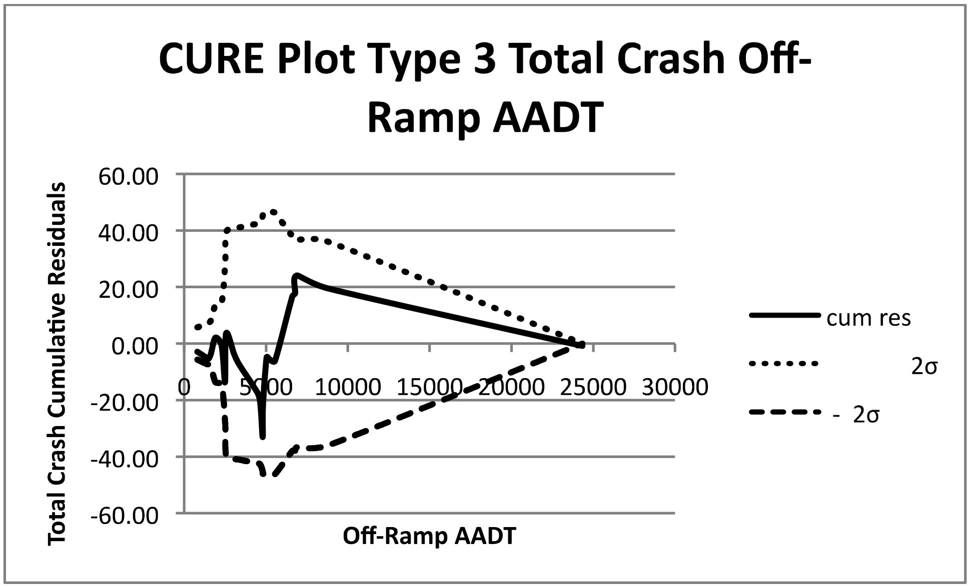
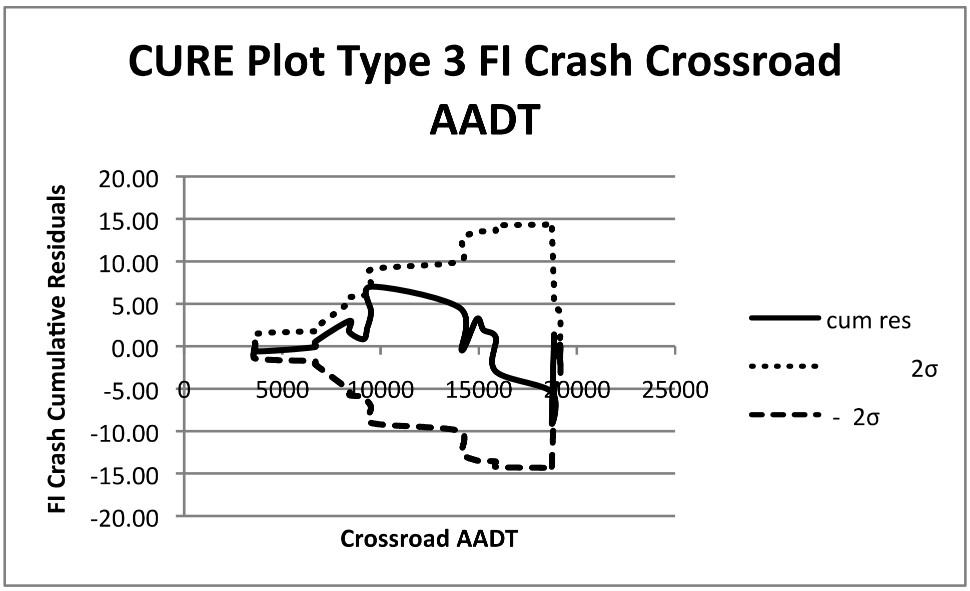
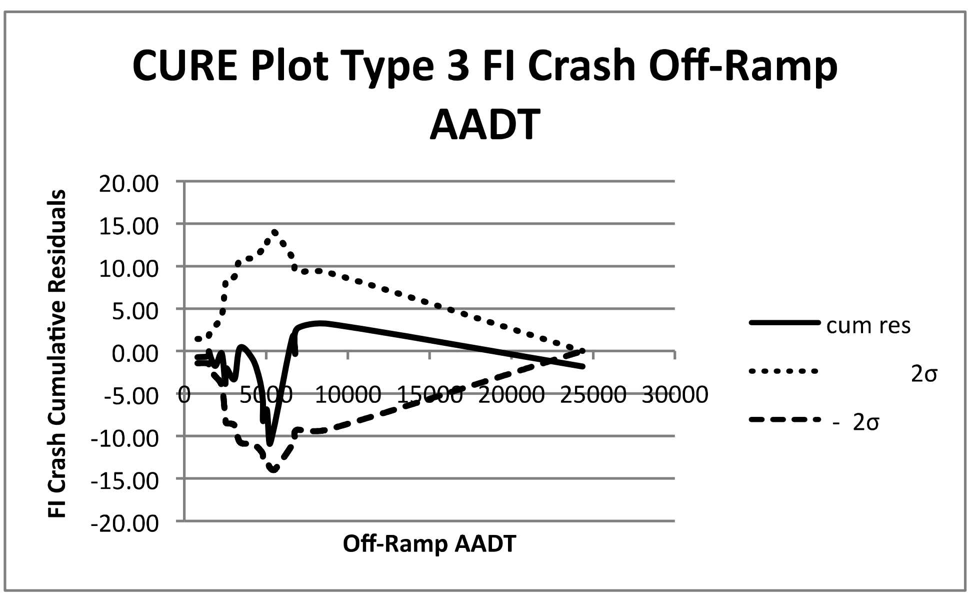
40.00
20.00
0.00
-20.00
-40.00
-60.00
0
5000
10000
15000
20000
25000
Crossroad AADT
cum res
2σ
- 2σ



CURE Plot Type 3 Total Crash Off-Ramp AADT
Total Crash Cumulative Residuals
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
0
5000
10000
15000
20000
25000
30000
Off-Ramp AADT
cum res
2σ
- 2σ



CURE Plot Type 3 FI Crash Crossroad AADT
FI Crash Cumulative Residuals
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
5000
10000
15000
20000
25000
Crossroad AADT
cum res
2σ
- 2σ



CURE Plot Type 3 FI Crash Off-Ramp AADT
FI Crash Cumulative Residuals
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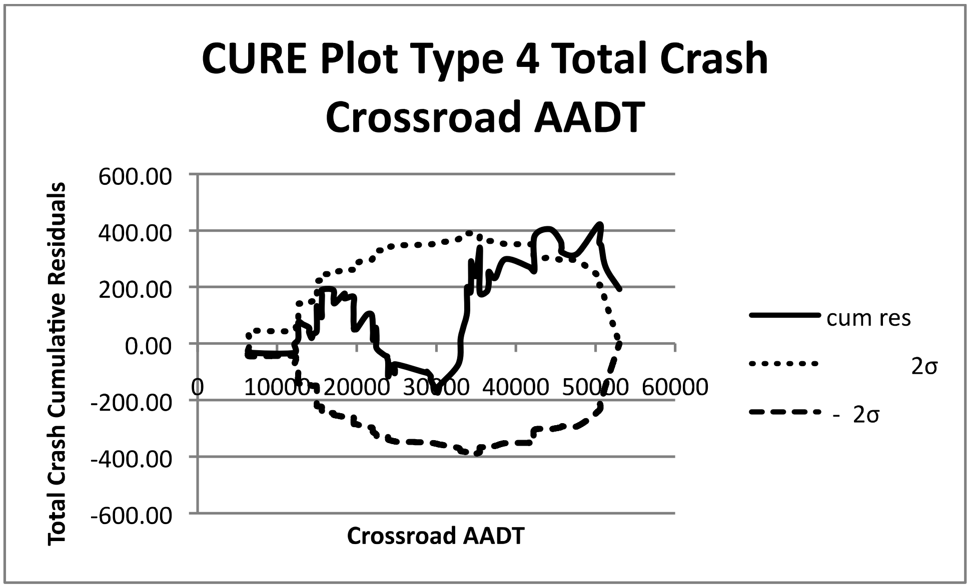
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
5000
10000
15000
20000
25000
30000
Off-Ramp AADT
cum res
2σ
- 2σ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Total Crash Cumulative Residuals
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200.00
0.00
-200.00
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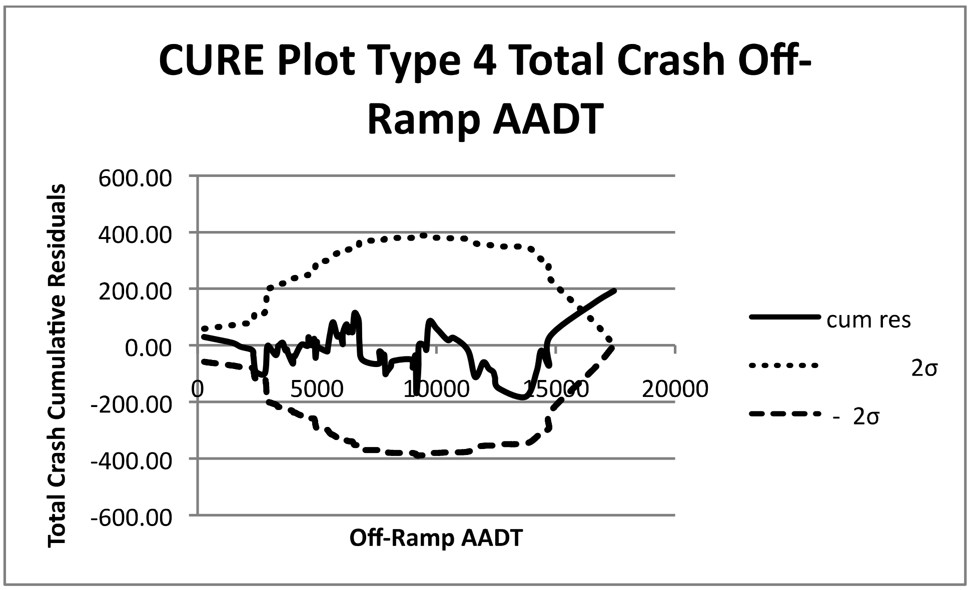
0
10000
20000
30000
40000
50000
60000
Crossroad AADT
cum res
2σ
- 2σ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Total Crash Cumulative Residuals
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200.00
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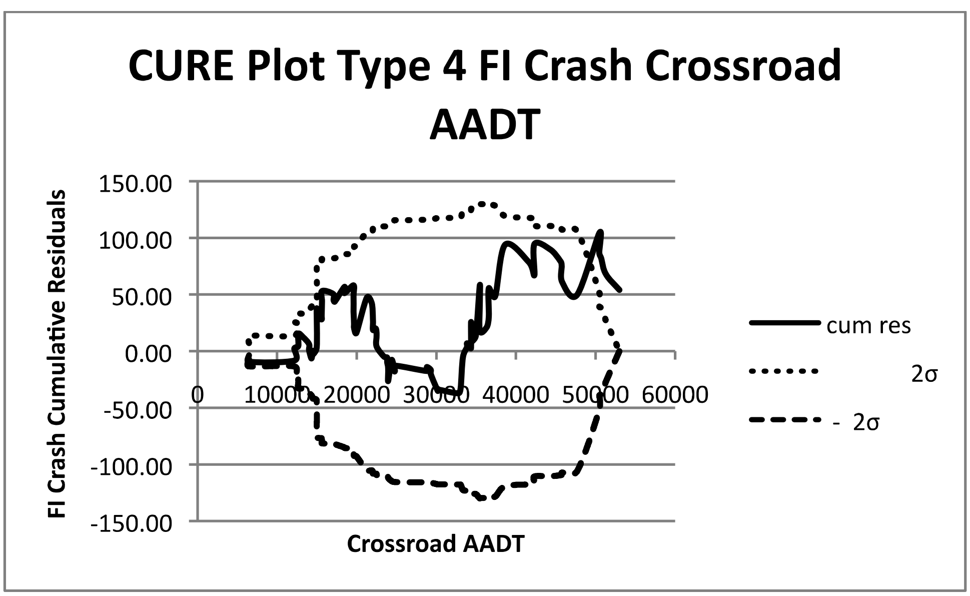
-600.00
0
5000
10000
15000
20000
Off-Ramp AADT
cum res
2σ
- 2σ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50.00
0.00
-50.00
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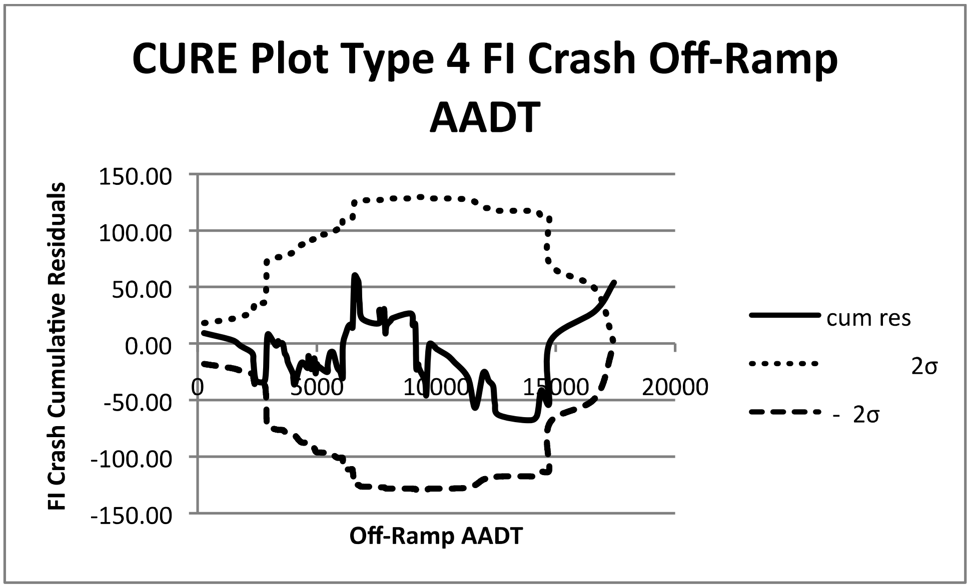
60000
Crossroad AADT
cum res
2σ
- 2σ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FI Crash Cumulative Residuals
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50.00
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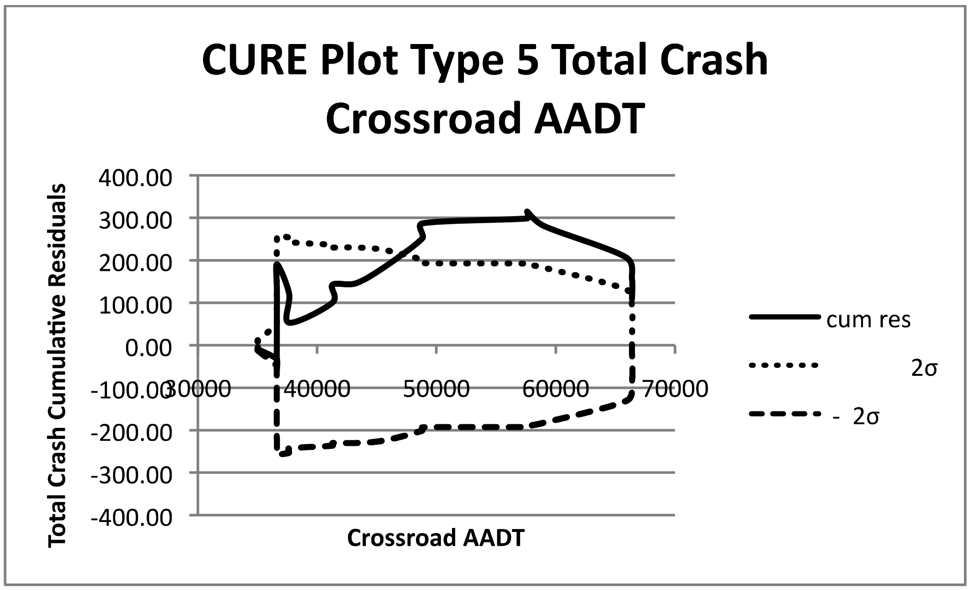
-50.00
-100.00
-150.00
0
5000
10000
15000
20000
Off-Ramp AADT
cum res
2σ
- 2σ


CURE Plot Type 5 Total Crash Crossroad AADT
Total Crash Cumulative Residuals
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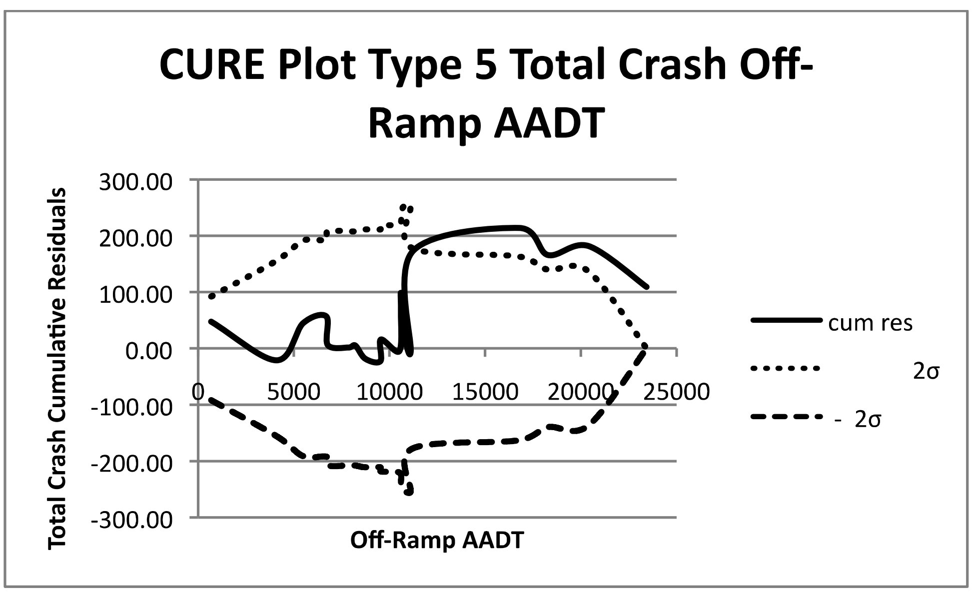
300.00
200.00
100.00
0.00
-100.00
-200.00
-300.00
-400.00
30000
40000
50000
60000
70000
Crossroad AADT
cum res
2σ
- 2σ


CURE Plot Type 5 Total Crash Off-Ramp AADT
Total Crash Cumulative Residuals
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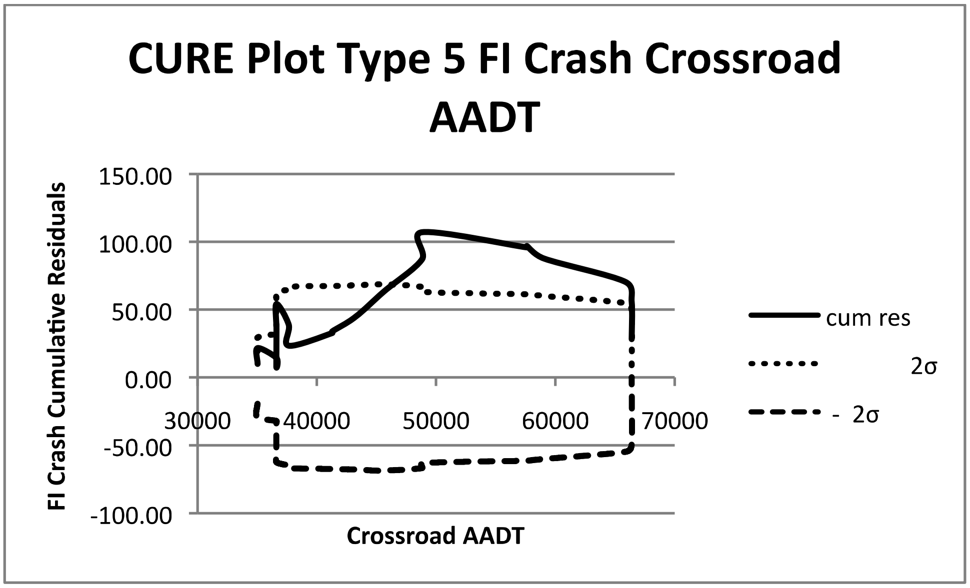
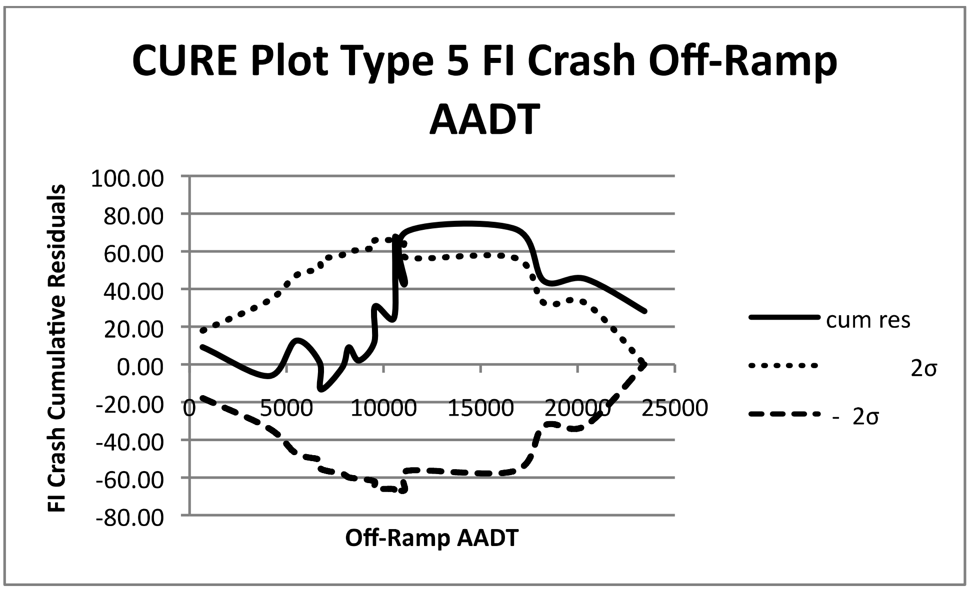
200.00
100.00
0.00
-100.00
-200.00
-300.00
0
5000
10000
15000
20000
25000
Off-Ramp AADT
cum res
2σ
- 2σ


CURE Plot Type 5 FI Crash Crossroad AADT
150.00
100.00
50.00
0.00
-50.00
-100.00
30000
40000
50000
60000
70000
FI Crash Cumulative Residuals
Crossroad AADT
cum res
2σ
- 2σ


CURE Plot Type 5 FI Crash Off-Ramp AADT
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
0
5000
10000
15000
20000
25000
FI Crash Cumulative Residuals
Off-Ramp AADT
cum res
2σ
- 2σ

APPENDIX C: MODEL PLOTS

The models were all plotted for the crossroad AADT data range using mid-range off-ramp AADTs of 2,000 for unsignalized intersections and 7,500 for signalized intersections. Both total and fatal+injury (FI) crashes are plotted. Also plotted are comparable models from the ISAT tool[4]. The ISAT models are not specific to diamond interchanges but are all 4-leg ramp terminals. Separate models are available for urban and rural environments. These models are described below. In all models 'maj' and 'min' refer to the major and minor road AADTs respectively.

Rural 4 leg Stop-Controlled

Total Crashes per year = $\exp(-8.96)maj^{.65}min^{.47}$

FI Crashes per year = $\exp(-9.36)maj^{.66}min^{.40}$

Urban 4 leg Stop-Controlled

Total Crashes per year = $\exp(-3.12)maj^{.27}min^{.16}$

FI Crashes per year = $\exp(-4.35)maj^{.29}min^{.19}$

Rural 4 leg Signalized

Total Crashes per year = $\exp(-6.57)maj^{.66}min^{.20}$

FI Crashes per year = $\exp(-7.83)maj^{.75}min^{.14}$

Urban 4 leg Signalized

Total Crashes per year = $\exp(-3.47)maj^{.42}min^{.14}$

FI Crashes per year = $\exp(-5.11)maj^{.49}min^{.16}$

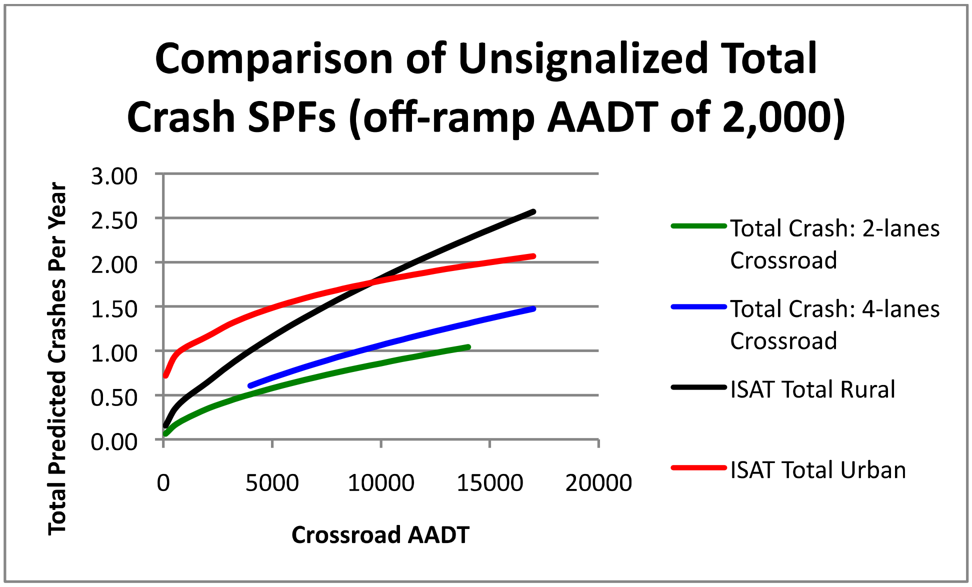
Bearing in mind that these plots pertain to a specific ramp AADT value, the following general conclusions can be drawn from them:

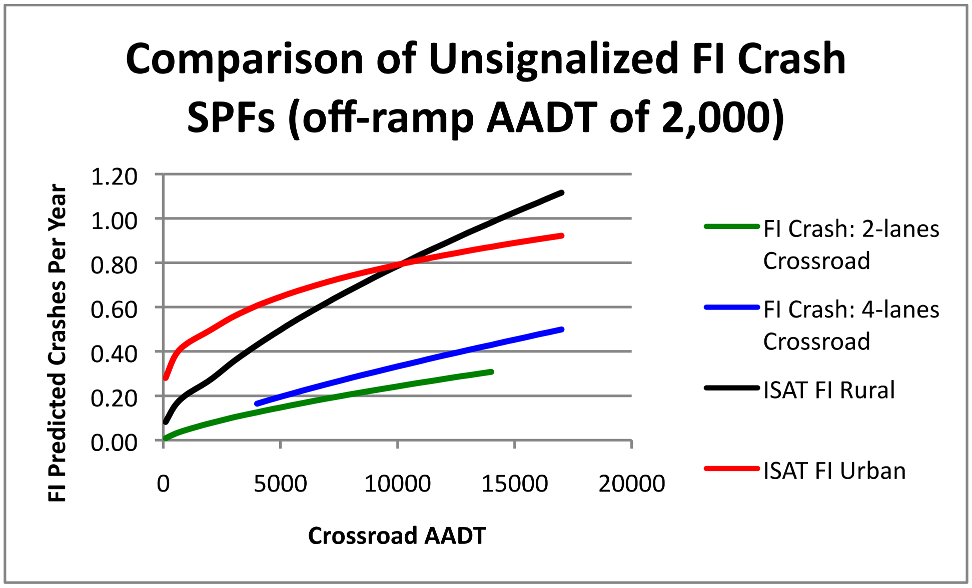
---

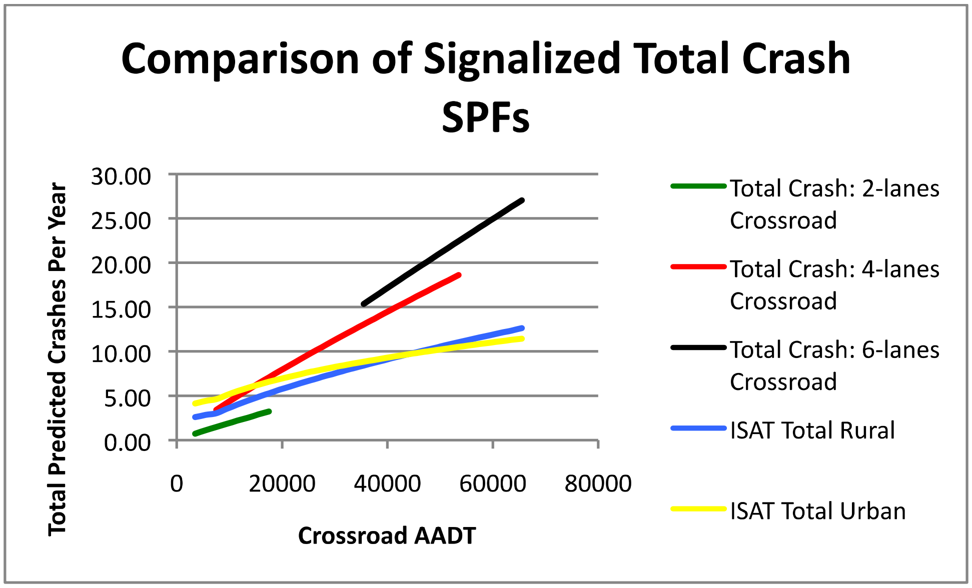
4 Torbic, D. Harwood, D., Gilmore, D. and K. Richard. Interchange Safety Analysis Tool (ISAT): User Manual. FHWA-HRT-07-045. http://www.tfhrc.gov/safety/pubs/07045/07045.pdf

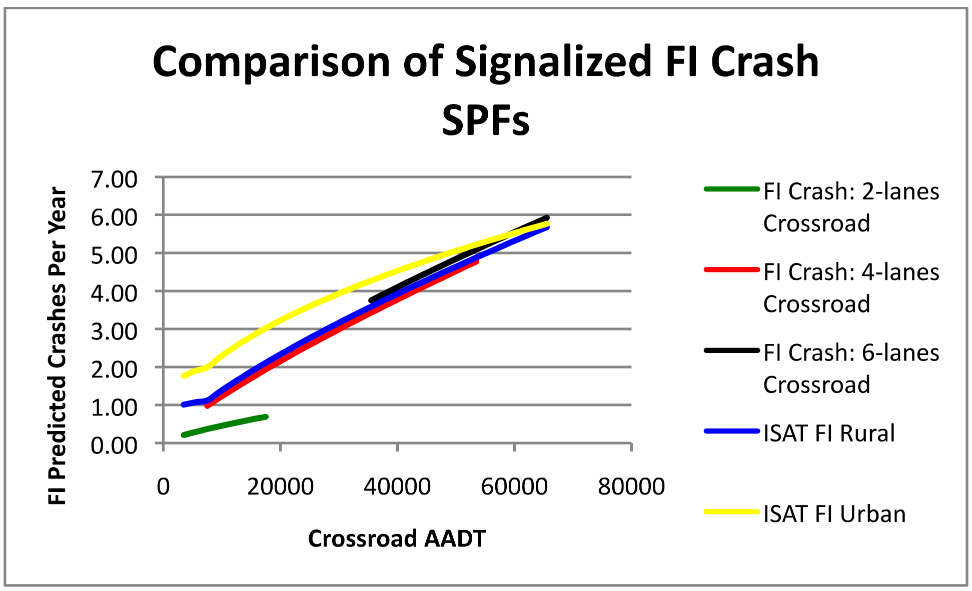
- For unsignalized intersections, the ISAT models predict substantially more collisions that the Colorado SPFs. The correspondence is much closer for signalized intersections.

- For Colorado, the SPFs indicate more collisions for crossroads with more lanes. This may be a reflection of higher speeds or speed limits on crossroads with more lanes.






Comparison of Signalized Total Crash SPFs
Total Predicted Crashes Per Year
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
20000
40000
60000
80000
Crossroad AADT
Total Crash: 2-lanes Crossroad
Total Crash: 4-lanes Crossroad
Total Crash: 6-lanes Crossroad
ISAT Total Rural
ISAT Total Urban


Comparison of Signalized FI Crash SPFs
FI Predicted Crashes Per Year
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
20000
40000
60000
80000
Crossroad AADT
FI Crash: 2-lanes Crossroad
FI Crash: 4-lanes Crossroad
FI Crash: 6-lanes Crossroad
ISAT FI Rural
ISAT FI Urban

APPENDIX D: COMPARABLE MODELS FOR ONTARIO[5]

SPFs were calibrated for four ramp terminal categories using various variables. The categories were:

- Three-legged signalized
- Four-legged signalized
- Three-legged stop-controlled
- Four-legged stop-controlled

For signalized intersections, the SPF form is:

$$(Acc / year)_i = a(AADTramp_i)^b (AADTcross)_i^c e^{d(dummy)}$$

where,
AADTcross is the sum of approach volumes from two approaches of the side road
AADTramp is the sum of approach volumes from ramp and the service roads
AADTtotal is the total AADT approaching the terminal from all approaches
'dummy' is a dummy variable taking a value of zero if the approach ramp is not split and 1 if the approach ramp is split to provide a separate right turn lane with yield control.

For stop-controlled intersections, the SPF form is:

$$(Acc / year)_i = a(AADTtotal)_i^b e^{c(dummy)}$$

Intersection Category	Collision type	Parameter	Estimate	Std. Error	P-value
3-Legged Signalized 140 Sites	FI	ln(a)	-12.7762	1.9129	0.0001
		b	0.6187	0.1776	0.0005
		c	0.6114	0.1946	0.0017
		d	-0.7555	0.1478	0.0009
		Dispersion	0.8132	0.1072	-
	PDO	ln(a)	-11.5143	1.312	0.0001
		b	0.7360	0.1123	0.0001
		c	0.5351	0.1181	0.0001
		d	-0.7636	0.1465	
		Dispersion	0.4257	0.0606	-

5 Parajuli B., Persaud B., Lyon C. and Munro J. "Safety Performance Assessment of Freeway Interchanges, Ramps and Ramp Terminals". Proceedings, Transportation Association of Canada Annual Conference, PEI 2006.

Intersection Category	Collision type	Parameter	Estimate	Std. Error	P-value
4-Legged Signalized 23 Sites	FI	ln(a)	-17.1286	3.9417	0.0001
		b	0.7150	0.2558	0.005
		c	0.9685	0.4299	0.02
		d	-2.4316	1.0432	0.01
		Dispersion	0.1501	0.1235	-
	PDO	ln(a)	-14.4269	4.1520	0.0001
		b	0.9566	0.2382	0.0001
		c	0.6219	0.4321	0.15
		d	-1.3896	0.4710	0.0032
		Dispersion	0.3328	0.1418	-
3-Legged and 4-Legged Stop-Controlled 144 Sites	FI	ln(a)	-6.9588	1.9920	0.0005
		b	0.5028	0.2077	0.015
		c	-1.1066	0.3405	0.0012
		Dispersion	1.173	0.4364	-
	PDO	ln(a)	-6.7506	1.2659	0.0001
		b	0.6087	0.1319	0.0001
		c	-1.0104	0.1976	0.0001
		Dispersion	0.5499	0.124	-