Final Report

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VALIDATION AND APPLICATION OF HIGHWAY SAFETY MANUAL (PART D) AND DEVELOPING FLORIDA CMF MANUAL, Phase 2

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

UNIT CONVERSION

SI*Modern Metric Conversion Factors as provided by the Department of Transportation, Federal Highway Administration http://www.fhwa.dot.gov/aaa/metricp.htm

LENGTH				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

AREA				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

LENGTH				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

AREA				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E3.

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16. Abstract

The Highway Safety Manual (HSM) Part D provides a comprehensive list of the effects of safety treatments (countermeasures). These effects are quantified by crash modification factors (CMF) which are based on compilation from past studies of the effects of various safety treatments. The HSM Part D provides CMFs for treatments applied to roadway segments, intersections, interchanges, freeways, and special facilities. Nevertheless, it is essential to verify the applicability of the HSM CMFs in specific locales.

The objectives of this study are (1) to develop CMFs for various treatments in Florida for the same setting (rural/urban), road types, crash types, and severity levels, (2) to evaluate the difference between these Florida-specific CMFs and the CMFs in the HSM, and (3) to recommend whether the CMFs in the HSM can be applied to Florida or new Florida-specific CMFs are needed. Moreover, in phase II, various Florida-specific CMFs and crash modification functions (CMFunctions) were estimated for the most common treatments in Florida. As with phase I of the project, there is a need to improve some CMFs that had insufficient data. An alternative way to combine multiple CMFs to identify the effectiveness of multiple treatments was suggested in this study.

Different methods of observational studies were used to calculate CMFs and to develop CMFunctions for a total of 37 additional treatments applied to roadway segments, intersections and special facilities. It was found that Florida-specific CMFs were generally statistically significant, and the safety effects represented by the CMFs were intuitive, similar to the CMFs in the HSM. It was also found that Florida-specific CMFs for the treatments not included in the HSM showed significant positive effects in reducing crash frequencies. We also present a Florida-specific manual of CMFs.

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EXECUTIVE SUMMARY

The Highway Safety Manual (HSM) (AASHTO, 2010) was developed by the Transportation Research Board (TRB) to provide analytical methods to quantify the safety effects of decisions and treatments in planning, design, operation, and maintenance. The HSM will enable officials to benefit from the extensive research in safety of highways as it bridges the gap between research and practice. An assessment of the applicability of this manual in Florida is essential. Among the four main sections in the HSM, part D, which is a compilation from past studies of the effects of various safety treatments (i.e., countermeasures), provides a variety of crash modification factors (CMFs).

The objectives of the first phase of this study were (1) to develop CMFs for various treatments in Florida for the same setting (rural/urban), road type, crash type, and severity level in the HSM, (2) to evaluate the difference between these Florida-specific CMFs and the CMFs in the HSM, and (3) to recommend whether the CMFs in the HSM can be applied to Florida or new Florida-specific CMFs are needed. Different methods of observational studies – Before-After (BA) and Cross-Sectional (CS) – were used to calculate CMFs for a total of 17 treatments applied to roadway segments, intersections, and special facilities. The methods of calculating CMFs were determined based on the availability of the data and the methods used in the HSM if the CMFs are provided in the HSM. The list of 17 treatments that are included in phase I and the methods used to calculate the CMFs are as follows:

1. Roadway Segments (* denotes the treatment not included in the HSM):

1) Adding a through lane*;
2) Adding shoulder rumble strips on two-lane undivided roadways*;
3) Adding shoulder rumble strips on rural multilane roads;
4) widening shoulder width on rural multilane roads*;
5) Combined shoulder rumble strips + widening shoulder width on rural multilane roads*;
6) Converting a two-way left-turn lane to a raised median;
7) Adding lighting;
8) Adding a raised median;
9) Increasing median width;
10) Narrowing lane width;
11) Converting 4 to 3 lanes;
12) Narrowing paved right shoulder width;
13) Adding a bike lane*.

2. Intersections and Special Facilities (* denotes the treatment not included in the HSM):
    14) Signalization of stop-controlled intersections;
    15) Adding left turn lanes;
    16) Adding red light running cameras;
    17) Converting traditional mainline toll plazas to hybrid mainline toll plazas*.

The estimated Florida-specific CMFs were generally statistically significant and the safety effects represented by the CMFs were intuitively similar to the CMFs in the HSM. It was found that Florida-specific CMFs for the treatments not included in the HSM show significant positive effects in reducing crash frequencies. In conclusion, Florida-specific CMFs developed in this study are recommended for application to Florida as long as they are statistically significant and have smaller standard errors.

Although phase I of this study evaluated the validity of many of the CMFs for the treatments included in the HSM, there are still some treatments that have not been analyzed. Based on the Florida financial reports, which show the most common projects in Florida, and the availability of Florida-specific data, the safety effects for the following treatments have been estimated in phase II:

1. Roadway Segments (* denotes the treatment not included in the HSM):
    1) Adding Shoulder Rumble Strips on Rural Two-lane Roadways
    2) Widening Shoulder Width on Rural Two-lane Roadways*;
    3) Adding Shoulder Rumble Strips + Widening Shoulder Width on Rural Two-lane Roadways*;
    4) Changing Lane Width at Straight and Curved Rural Two-lane Roadways*;
    5) Changing Shoulder Width at Straight and Curved Rural Two-lane Roadways*;
    6) Installation of Median Barriers on Rural Multilane Roadways;
    7) Increasing the Distance to Roadside Poles on Rural Multilane Roadways*;
    8) Increasing the Distance to Roadside Trees on Rural Multilane Roadways*;
    9) Decreasing Density of Driveways on Rural Multilane Roadways *;
    10) Decreasing Density of Roadside Poles on Rural Multilane Roadways*;
    11) Changing Lane Width on Rural Multilane Roadways;
    12) Decreasing School Zone Speed Limits on Segments in School Zone Area on Rural + Urban Roadways*;
    13) Increasing Shoulder Width on Segments in School Zone Area on Urban Arterials*;
    14) Changing School Zone Speed Limits on Segments in School Zone Area on Urban Arterials*;
    15) Installation of Flashing Beacon at School Zone Signs in School Zone Area on Urban Arterials*;

16) Decreasing Number of Driveways on Segments in School Zone Area on Urban Arterials*;
17) Widening Urban 4- to 6-lane Roadways*;
18) Increasing Lane Width on Urban Arterials*;
19) Increasing Shoulder Width on Urban Arterials*;
20) Increasing Median Width on Urban Arterials;
21) Increasing Bike Lane Width on Urban Arterials*;
22) Lane Reduction on Urban Arterials*;
23) Adding a Bike lane + Lane Reduction on Urban Arterials*;
24) Resurfacing Urban Arterials*;
25) Adding Shoulder Rumble Strips on Freeways;
26) Adding Lanes by Narrowing Existing Lane and Shoulder Widths on Freeways;
27) Installation of Roadside Barriers on Freeways*;
28) Increasing Shoulder Width on Freeways*;
29) Installation of Roadside Barriers + Increasing Shoulder Width on Freeways*;

2. Intersections and Special Facilities:
    30) Converting a Minor-road Stop-controlled Intersection to a Modern Roundabout*;
    31) Adding Right Turn Lane;
    32) Adding Left Turn Lane;
    33) Changes of Median Width on Signalized Intersection*;
    34) Changes of Intersection Angle Level;
    35) Installation of Retro-Reflective Border Back Plates*;
    36) Installation of Red Light Running Warning Sign with Citation Amount Specified at Upstream of the Intersection*;
    37) Converting Traditional and Hybrid Toll Plazas to All Electronic Toll Collection*;
    38) Converting HOV Lanes to HOT Lanes*;

During our research, we have found that in many situations, CMFs are very simplistic abstractions, and there is a need to develop crash modification functions (CMFunctions). Since the CMF is a single value which represents the average safety effect of the treatment for all treated sites, the heterogeneous effects of roadway characteristics on CMFs among treated sites are ignored. To overcome this limitation, it is recommended to develop CMFunctions to predict the variation in CMFs based on the site characteristics. Moreover, in phase I, combining multiple CMFs was addressed to identify the effectiveness of multiple treatments. This issue is not well addressed in the HSM as the recommendation there is merely multiplying all CMFs, which overestimate the effect. Therefore, this is another issue that needs to be assessed. Lastly, a larger sample in phase II would reduce the error in any estimates in Phase I that had restricted data.

The main objectives of this second phase of the project could be summarized as follows:

1. Identify the most common treatments in Florida
2. Produce additional important CMFs
3. Produce CMFunctions for the same treatments for more accurate representation of the safety effects of the treatments.
4. Calculate the safety effectiveness of combined treatments commonly applied in Florida
5. Improve and finalize some of the analyses produced in Phase I if more samples are available.
6. Produce a Florida CMF manual based on Phases I and II for application by engineers in Florida

It was found that the Florida-specific CMFs were generally statistically significant, and safety effects represented by the CMFs were intuitive similar to the CMFs in the HSM. It was also found that Florida-specific CMFs for the treatments not included in the HSM show significant positive effects in reducing crash frequencies. Thus, these treatments need to be considered in addition to the treatments included in the HSM. Moreover, the developed CMFunctions provided the variation of CMFs based on different roadway characteristics, time trends, etc. Lastly, the proposed combining approach to assess the combined safety effects of multiple CMFs produced the most accurate and reliable combined CMFs compared to the actual safety effects of multiple treatments.

In conclusion, Florida-specific CMFs developed in this study are recommended for application to Florida as long as they are statistically significant. However, if they are not significant, the CMFs in the HSM (if they are significant) are recommended. The developed CMFunctions can be applied to reflect the changes of safety effects based on different roadway characteristics. Also, it can be recommended that the safety effects of multiple treatments are estimated using the newly suggested approach for combining multiple CMFs to (1) overcome the over-estimation issue, (2) account for different severity levels and roadway types, (3) consider negative and relatively higher CMF values, and (4) enhance the reliability of combined effectiveness of multiple treatments.

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LIST OF ACRONYMS/ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AETC	All Electronic Toll Collection
AHP	Analytic Hierarchy Process
ARMA	Autoregressive Moving Average
BA	Before-After
BF	Basis Function
BIC	Bayesian Information Criterion
CARS	Crash Analysis Reporting System
CG	Comparison Group
CMF	Crash Modification Factor
CMFunction	Crash Modification Function
CRF	Crash Reduction Factor
CS	Cross-sectional
DIC	Deviance Information Criterion
DOT	Department of Transportation
EB	Empirical Bayes
EEACF	Excess Expected Average Crash Frequency
FB	Full Bayes

FHWA	Federal Highway Administration
FI	Fatal and Injury
FDOT	Florida Department of Transportation
FM	Financial Management
FPS	Financial Project Search
FT	Florida Turnpike
GCV	Generalized Cross-validation
GIS	Geographic Information System
GNM	Generalized Nonlinear Models
HMTP	Hybrid Mainline Toll Plaza
HOT	High-Occupancy Toll Lanes
HOV	High-Occupancy Vehicle Lanes
HSM	Highway Safety Manual
ISs	Influential Segments
LOS	Level of Service
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
MARS	Multivariate Adaptive Regression Splines
MCDM	Multi Criteria Decision Making
MCMC	Monte Carlo Markov Chain
MVM	Million Vehicle Miles

NCHRP	National Cooperative Highway Research Program
NB	Negative Binomial
OP	Observed-Prediction
PDO	Property Damage Only
RCI	Roadway Characteristics Inventory
ROR	Run-off-the-road
RV	Recreational Vehicle
SE	Standard Error
SLD	Straight Line Diagram
SVROR	Single Vehicle Run-off-the-road
SPF	Safety Performance Function
SRS	Shoulder Rumble Strips
TBP	Toll by Plate
TMTP	Traditional Mainline Toll Plaza
TRB	Transportation Research Board
TWLTL	Two-Way Left-Turn Lane
WLS	Weighted Least Square
WSW	Widening Shoulder Width

CHAPTER 1. INTRODUCTION

The Highway Safety Manual (HSM) (AASHTO, 2010) provides analytical methods to evaluate the effects of safety treatments (countermeasures). These can be quantified by what is known as crash modification factors (CMFs). HSM Part D, based on literature review and in the input of experts, lists CMFs or at least trends (or unknown effects) for each treatment. The HSM presents a variety of technical approaches and methods for analysis of highway safety effects. CMFs have been estimated using observational before-after studies that account for the regression-to-the-mean bias. Moreover, the cross-sectional method has been commonly used to derive CMFs since the required data is easier to collect compared to before-after methods. CMFs are expressed as numerical values together with standard error to express the percent increase or decrease in crash frequency. A standard error of 0.10 or less indicates that a CMF is sufficiently accurate (AASHTO, 2010). CMFs could also be expressed as a function (or equation), graph, or combination.

HSM Part D provides CMFs for roadway segments (e.g., roadside elements, alignment, lighting, rumble strips, etc.), intersections (e.g., signal control, turning lanes, etc.), interchanges, special facilities (e.g., toll plaza), and road networks. CMFs could be applied individually if a single treatment is proposed or multiplied if multiple treatments are implemented. Due to the lack of sufficient CMFs of multiple treatments, the HSM suggests that CMFs can be multiplied to estimate the combined safety effects of single treatments. However, the HSM cautions that the multiplication of the CMFs may over- or under-estimate combined effects of multiple treatments.

Moreover, the CMF estimated by before-after studies represents overall safety effects of the treatment in a fixed value. However, as each treated site has different roadway characteristics, there is a need to assess the variation of CMFs among the treated sites with different roadway characteristics through development of crash modification functions (CMFunctions).

In order to estimate accurate expected crash frequency of both the existing and proposed roadway conditions, the HSM suggests to 1) apply predictive method (i.e., safety performance function (SPF)) in Part C to estimate the predicted average crash frequency of existing condition and 2) use (multiply) appropriate crash modification factors (CMFs) in Part D to predict the average crash frequency of the proposed condition, simultaneously. It should be noted that the HSM provides various CMFs for single treatments, but not CMFs for multiple treatments to roadway segments and intersections. Due to the lack of sufficient CMFs of multiple treatments in the HSM and CMF Clearinghouse (FHWA, 2013), it is suggested to use a method (i.e., multiplication of CMFs) to combine multiple CMFs (AASHTO, 2010). However, the HSM also cautioned that the predictive approach using the SPFs and CMFs in the HSM does not guarantee reliable results because the multiplication of CMFs might over- or under-estimate the number of predicted crashes.

The CMFs can therefore play a vital role as an important tool to enable practitioners in Florida Department of Transportation (FDOT) to estimate the safety effects of various single and multiple countermeasures. In addition, practitioners could identify the most cost-effective strategies to reduce the number of crashes at all levels (or severe crashes) at problematic locations. This report helps practitioners checking the validity of assumptions in cost-benefit analyses. Also, CMFunctions can provide insights into treatments design (e.g., width of bike lane) and selection of sites (e.g., urban four-lane undivided roadways with specific Annual Average Daily Traffic (AADT) ranges) for specific treatment. Lastly, an alternative approach to combine multiple CMFs can estimate more reliable predicted number of crashes. Thus, it is important to come up with the Florida CMF manual by addition of most common and important CMFs and CMFunctions based on FL data. Figure 1-1 provides diagram for project plan. In this report, crash severities were categorized according to the KABCO scale as follows: fatal (K), incapacitating injury (A), non-incapacitating injury (B), possible injury (C) and property damage only (O).

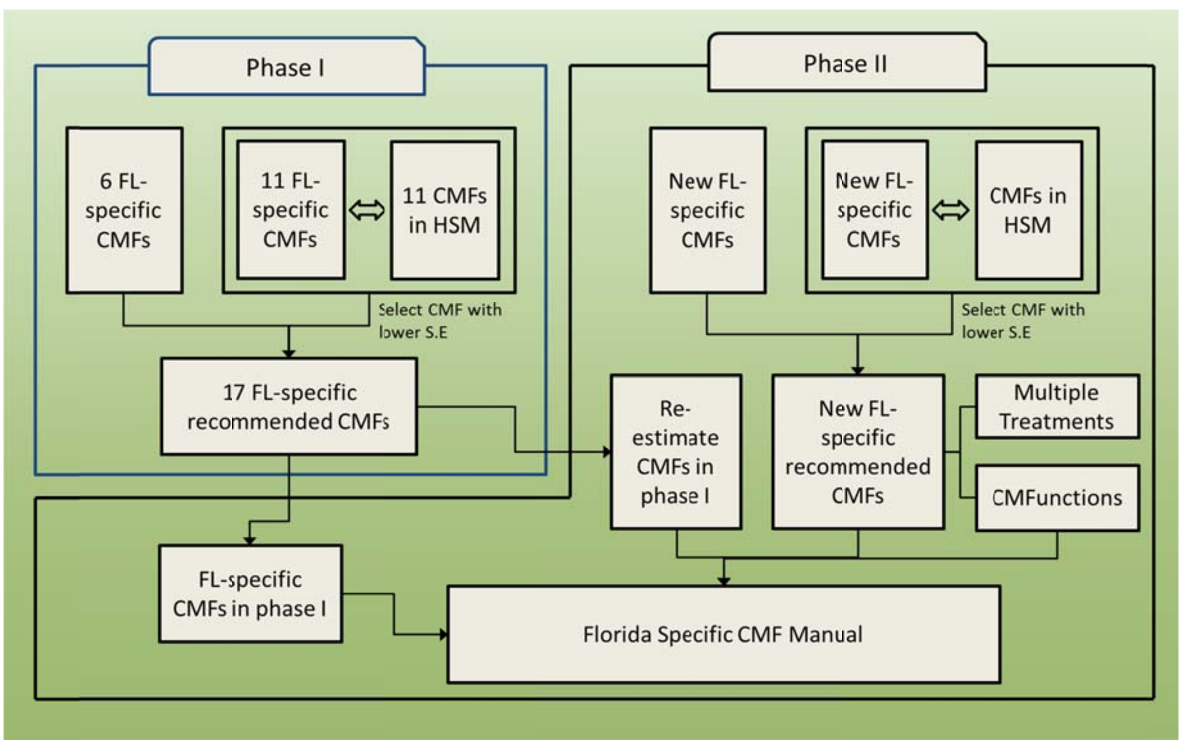


Figure 1-1: Project Plan Diagram

CHAPTER 2. LITERATURE REVIEW

The HSM published in 2010 perfectly bridge the gap between traffic safety researches and safety improvement applications for the highways. One of the key parts in this manual is the SPF and the CMFs, which can help local agencies and DOTs to discover the hot spots (locations with high crash occurrences) and suggest countermeasures for sites of concern. However, the basic method stated in the HSM was calibrated only based on several states and it need further calibration before applied to a specific area, the calibration factor should be calculated to develop jurisdiction specific models.

2.1 Latest Studies Related to the HSM and Crash Modification Factors

Alkhatni et al (2014) examined the effects of presence of weigh stations on injury severity and frequency of crashes on Michigan freeways. The study investigated crash patterns in the vicinity of 12 fixed weigh stations as compared to crash patterns in the vicinity of 65 rest areas and 77 selected comparison segments. Three major influential segments (ISs) were identified: before facility, at facility, and after facility. Comparison segments with similar traffic and geometric characteristics as the ISs were also identified. The result indicates that presence of fixed weigh station is shown to have positive impact. This indicates that crashes occurring near fixed weigh stations tend to be more severe than those occurring at rest areas and comparison segments.

Chen et al (2014) investigated the safety performance of short left-turn lanes at unsignalized median openings. Six years of crash data were collected from fifty-two median left turn lanes in

Houston, Texas, which included forty short lanes and twelve lanes. A Poisson regression model was developed to relate traffic and geometric attributes to the total count of rear-end, sideswipe, and object-motor vehicle crashes at a left-turn lane. CMFs were calculated for future applications in projecting the crash frequency, given a specific change of the lane length. It was statistically evidenced that the difference between actual lane length and the Greenbook recommended length had significant effects on the crash frequency. The CMF is found to be 2.32 if a left-turn lane is 20 percent shorter than what is suggested in the Greenbook.

Dell'Acqua et al (2014) identified the modeling results between HSM and the situation in Italy. This is paper implement the model to assess crash behavior in Italy. To adjust the base predicted crash frequency to meet the current conditions, the CMFs calculation for lane width, horizontal curve and vertical grade were identified. Crash types (head-on/side collisions, single-vehicle crashes, rear-end collisions) were investigated based on the vertical grade and the curvature indicator. The result of this paper shows calibration factor is 0.477 when applying to Italy.

Khan et al (2014) assessed the safety effectiveness of shoulder rumble strips in reducing run-off-the-road (ROR) crashes on two-lane rural highways using the observational before and after with empirical Bayes (EB) method. The comprehensive procedure adopted for developing the safety performance function of EB analysis also considers the effects of roadway geometry and paved right shoulder width on the effectiveness of shoulder rumble strips. The results of this study demonstrate the safety benefits of shoulder rumble strips in reducing the ROR crashes on two-lane rural highways using the State of Idaho 2001-2009 crash data. The study finds a 14% reduction in all ROR crashes after the installation of shoulder rumble strips on 178.63 miles of two-lane rural highways in Idaho. The results indicate that shoulder rumble strips were most effective on roads with relatively moderate curvature and right paved shoulder width of 3 feet and more.

Li et al (2014) tried to ensure a high level of road safety based on the best knowledge available of the effects of the road network planning. The authors looked into how changes in road network characteristics affect road casualties. To estimate the safety effectiveness of roadway networking, the full Bayes (FB) method was conducted. Also the authors applied a panel semi-parametric model to estimate the dose-response function for continuous treatment variables. The result suggests that there are more casualties in the area with a better connectivity and accessibility, where more attention should be paid to the safety countermeasures.

Mohammadi et al (2014) evaluated the changes in motor vehicle crashes that occurred on the Missouri interstate highway system. In this paper, the author applied EB methods to estimate safety effect as a result of countermeasures. The research associated crashes with traffic and roadway characteristics. Negative binomial (NB) models were developed for the before-after-change conditions. The models developed for the various collision types and crash severities were used to estimate the expected number of crashes at roadway segments in 2008, assuming with and without the implementation. This procedure estimated significant reductions of 10% in the overall number of crashes and a 30% reduction for fatal crashes. Reductions in the number of different collision types were estimated to15 be 18-37%. The results indicate that the policy reduces the number of crashes and decreasing fatalities by reducing the most severe collision types like head-on crashes.

Zeng et al (2014) evaluated evaluate the safety effectiveness of good pavement conditions versus deficient pavement conditions on rural two-lane undivided highways in Virginia. Using the EB method, it was found that good pavements are able to reduce fatal and injury (FI) crashes by 26 percent over deficient pavements, but do not have a statistically significant impact on overall crash frequency. The authors concluded that improving pavement from deficient to good condition can offer a significant safety improvement in terms of reducing crash severity.

Sacchi et al., (2012) studied the transferability of the HSM crash prediction algorithms on two-lane rural roads in Italy. The authors firstly estimated a local baseline model as well as evaluated each CMF based on the Italian data. Homogenous segmentation for the chosen study roads has been performed just to be consistent with the HSM algorithms. In order to quantify the transferability, a calibration factor has been evaluated to represent the difference between the observed number of crashes and the predicted number of crashes by applying HSM algorithm. With a four years crash data, the calibration factor came out to be 0.44 which indicate the HSM model has over predicted the collisions. After investigated the predicted values with observed values by different AADT levels, the authors concluded that the predicted ability of the HSM model for higher AADT is bad and a constant value of "calibration factor" is not appropriate. This effect was also proved from the comparison between the HSM baseline model and the local calculated baseline model. Furthermore, the authors evaluated CMFs for three main road features (horizontal curve, driveway density and roadside design). The calculation of CMFs has been grouped according to Original CMFs, and results of comparing the calculated CMFs to baseline CMFs indicated that the CMFs are not unsuitable for local Italian roadway characteristics since most of them are not consistent. Finally, several well-known goodness-of-fit measures have been used to assess the recalibrated HSM algorithms as a whole, and the results are consistent as the results mentioned in the split investigation of HSM base model and CMFs. With these facts the authors concluded that the HSM is not suitable to transferable to Italy roads and Europe should orient towards developing local SPFs/CMFs.

Sun et al., (2012) calibrated the SPF for rural multilane highways in the Louisiana State roadway system. The authors investigated how to apply the HSM network screening methods and identified the potential application issues. Firstly the rural multilane highways were divided into sections based on geometric design features and traffic volumes, all the features are distinct within each segment. Then by computing the calibration factor, the authors found out that the average calibration parameter is 0.98 for undivided and 1.25 for divided rural multilane highways. These results turned out that HSM has underestimated the expected crash numbers. Besides the calibration factor evaluation, the authors investigated the network screening methods provided by HSM. Thirteen methods are promoted in the HSM, each of these methods required different data and data availability issue is the key part of HSM network screening methods application. In the paper, four methods have been adopted: crash frequency, crash rates, excess expected average crash frequency using SPFs (EEACF) and expected average crash frequency with EB Adjustment (EACF). Comparisons between these methods have been done by ranking the most hazardous segments and findings indicate that the easily used crash frequency method produced similar results to the results of the sophisticated models; however, crash rate method could not provide the same thing.

Xie et al., (2011) investigated the calibration of the HSM prediction models for Oregon State Highways. The authors followed the suggested procedures by HSM to calibrate the total crashes in Oregon. In order to calculate the HSM predictive model, the author identified the needed data and came up with difficulties in collecting the pedestrian volumes, the minor road AADT values and the under-represented crash locations. For the pedestrian volume issue, the authors assumed to have “medium” pedestrian when calculate the urban signalized intersections. While for the minor road AADT issue, the authors developed estimation models for the specific roadway types. Then the calibration factors have been defined for the variety types of highways and most of these values are below than 1. These findings indicate an overestimation for the crash numbers by the HSM. However, the authors attribute these results to the current Oregon crash reporting procedures which take a relative high threshold for the Property Damage Only (PDO) crashes. Then for the purpose of proving the crash reporting issue, the authors compared the HSM proportions of different crash severity levels and the Oregon oriented values. Furthermore, calibration factors for fatal and injury crashes have been proved to be higher than the total crash ones, which also demonstrated that Oregon crash reporting system introduce a bias towards the fatal and injury conditions. So the authors concluded that the usages of severity-based calibration factors are more suitable for the Oregon State highways.

Howard and Steven (2012) investigated different aspects of calibrate the predictive method for rural two-lane highways in Kansas State. Two data sets were collected in this study; one data set was used to develop the different model calibration methods and the other one was adopted for evaluating the models accuracy for predicting crashes. At first, the authors developed the baseline HSM crash predictive models and calculated the Observed-Prediction (OP) ratios. Results showed a large range of OP ratios which indicate the baseline method is not very promising in predicting crash numbers. Later on, the author tried alternative ways to improve the model accuracy. Since crashes on Kansas rural highways have a high proportion of animal collision crashes which is nearly five times the default percentage presented in the HSM. The authors tried to come up with a (1) Statewide Calibration factor, (2) Calibration factors by crash types, (3) Calibration using animal crash frequency by county and (4) Calibration utilizing animal crash frequency by section. The observational before-after with EB method was introduced to see whether it would improve the accuracy and also a variety of statistical measures were performed to evaluate the performance. Finally, the authors concluded that the applications of EB method showed consistent improvements in the model prediction accuracy. Moreover, it was suggested that a single statewide calibration of total crashes would be useful for the aggregate analyses while for the project-level analysis, the calibration using animal crash frequency by county is very promising.

Banihashemi (2011) performed a heuristic procedure to develop SPFs and CMFs for rural two-lane highway segments of Washington State and compared the developed models to the HSM model. He utilized more than 5000 miles of rural two-lane highway data in Washington State and crash data for 2002-2004. Firstly Banihashemi proposed an innovative way to develop SPFs and CMFs, incorporating the segment length and AADT. Then CMFs for lane width, shoulder width, curve radius and grade have been developed. After all these procedures, Banihashemi came up with two self-developed SPFs and then compared them with the HSM model. The comparison was done at three aggregation levels: (1) each data group as single observation (no aggregation), (2) segments level with a minimum 10 miles length and (3) aggregated segments based on geometric and traffic characteristics of highway segments. A variety of statistical measures were introduced to evaluate the performances, and the author concluded that the results are comparable mostly, and there is no need to calibrate new models. Finally, a sensitivity analysis was conducted to see the influence of data size issue on the calibration factor for the HSM model, and the conclusions indicated that a dataset with at least 150 crashes per year is most preferred for Washington State.

Later, Banihashemi (2012) conducted a sensitivity analysis for the data size for calculating the calibration factors. Mainly, five types of highway segment and intersection crash prediction models were investigated: Rural two-lane undivided segments, rural two-lane intersections, rural multilane segments, rural multilane intersections, and urban/suburban arterials. Eight highway segment types were studied. Calibration factors were calculated with different subsets with variety percentages of the entire dataset. Furthermore, the probability that the calibrated factors fall within 5% and 10% range of the ideal calibration factor values was taken into account. Based on these probabilities, recommendations for the data size to calculate reliable calibration factors for the eight types of highways have been proposed. With the help of these recommendations, the HSM predictive methods can be effectively applied to the local roadway system.

Brimley et al., (2012) evaluated the calibration factor for the HSM SPF for rural two-lane two-way roads in Utah. Firstly, the authors used the SPF model stated in the HSM and found the calibration factor to be 1.16, which indicates an underestimate of crash frequency by the base model. Later, under the guidance of the HSM, the authors developed jurisdiction-specific NB models for the Utah State. More variables like driveway density, passing condition, speed limit and etc. were entered into the models with the p-values threshold of 0.25. Bayesian information criterion (BIC) was selected to evaluate the models and the finally chosen best promising model show that the relationships between crashes and roadway characteristics in Utah may be different from those presented in the HSM.

Zegeer et al., (2012) worked on the validation and application issues of the HSM to analysis of horizontal curves. Three different data sets were employed in this study: all segments, random selection segments and non-random selection segments. Besides, based on the three data sets, calibration factors for curve, tangent and the composite were calculated. Results showed that the curve segments have a relative higher standard deviation than the tangent and composite segments. However, since the development of a calibration factor requires a large amount of data collecting work, a sensitivity analysis of each parameter's influence for the output results for curve segments have been performed. HSM predicted collisions were compared as using the minimum value and the maximum value for each parameter. The most effective variables were AADT, curve radius and length of the curve. Other variables like grade, driveway density won't affect the result much if the mean value were utilized when developing the models. Finally, validation of the calibration factor was performed with an extra data set. Results indicated that the calibrated HSM prediction have no statistical significant difference with the reported collisions.

2.2 Previous Research Related to the Crash Modification Functions

There are few previous studies that have looked at the variation of CMFs based on different roadway characteristics or different conditions through estimation of CMFunctions. Elvik (2009) provides a framework to evaluate CMFunctions for the same or similar treatment by means of meta-regression analysis (Elvik, 2005) based on multiple studies. He estimated CMFunctions for installation of bypass and converting signalized intersections to roundabouts based on population changes. The results showed that the CMFs increasing with population for both treatments. However, fairly large amounts of data are needed to develop good CMFunctions.

Similar to this study, Elvik (2013) assessed the relationship between safety effects (accident rate) and radius of horizontal curves based on the studies from 10 different countries. The paper evaluates the summary crash modification function to assess the international transferability of national crash modification functions that have been estimated for the relationship between their accident rate and radius of curve. It was found that the estimated crash modification function appears to be a representative summary of these national functions. The results showed that accident rate increases as curve radius decreases and the relationship between accident rate and radius of curve appears to be the same in all countries.

Elvik (2011) applied six linear and non-linear functions to develop CMFunctions for speed enforcement. The CMFunction illustrates the effect of speed enforcement on the injury accidents as a function of the relative change in the level of speed enforcement. The results showed that increasing level of enforcement is associated with a reduction of accidents. The non-linear logarithmic function best fitted the data points from 13 previous studies but the inverse function also fitted the data well.

Sacchi et al., (2014) also claimed that using a single value of CMF may not be suitable to represent the variation in safety effects of the treatment over time. Thus, the authors developed CMFunctions to incorporate changes over time for the safety effectiveness of treatment. The Poisson-lognormal linear intervention and non-linear intervention models were developed and compared to find the best fitted function for the safety effects of the signal head upgrade program. However, the CMFunctions used in this study only account for changes in safety effects over time, but not different roadway characteristics of the treated sites. To overcome this limitation, Sacchi and Sayed (2014) estimated CMFunctions that accounted for AADT changes among treated sites and time trends using the same data for evaluation of the safety effectiveness of the signal head upgrade program.

2.3 Safety Effects of Multiple Treatments

There are very few studies on combined effects of multiple treatments. Bauer and Harwood (2013) evaluated the safety effect of the combination of horizontal curvature and percent grade on rural two-lane highways. Safety prediction models of five types of horizontal and vertical alignment combinations for fatal-and-injury and PDO crashes were developed and CMFs representing safety performance relative to level tangents were calculated from these models. According to Pitale et al., (2009), the safety effects of paving shoulders, widening paved shoulders (from 2ft to 4ft), and installing shoulder rumble strips on rural two-lane roadways are

16%, 7%, and 15% reductions in crash rates, respectively. Moreover, the result indicated a 37% reduction in crash rates associated with installing shoulder rumble strips + paving shoulders to segments with aggregate shoulders. However, these results were estimated by simply comparing crash rates between the before and after conditions.

Gross and Hamidi (2011) applied some of the above methods of combining multiple CMFs to calculate the CMF for shoulder rumble strips + widening shoulder. They combined CMFs for two single treatments (shoulder rumble strips and widening shoulder) from two different sources. They found that the combined CMFs calculated using the HSM method and Systematic reduction of subsequent CMFs method were similar to actual CMFs obtained from two different studies - Pitale et al., (2009) and Hanley et al., (2000). However, CMFs are likely to vary across different study areas even for the same treatment. Thus, combining CMFs obtained from different sources and comparing the combined CMF with actual CMFs from different studies do not clearly identify the best methods of combining multiple CMFs. Also, according to Hanley et al., (2000), some shoulder widening occurred in combination with installation of the rumble strips. However, the range of widening shoulder width was not specified in the study. Thus, there is a need to 1) compare the combined CMF with actual CMF for multiple treatments in the same study area and 2) ensure that roadway geometric conditions (e.g., range of widening shoulder width) are consistent among two treatments and their combination.

CHAPTER 3. METHODOLOGIES

3.1 Crash Modification Factors Development Methods

A CMF is known also as collision modification factor or accident modification factor (CMF or AMF), all of which have exactly the same function. Crash reduction factors (CRFs) function in a very similar way as they represent the expected reduction in number of crashes for a specific treatment. The proper calibration and validation of crash modification factors will provide an important tool to practitioners to adopt the most suitable cost effective countermeasure to reduce crashes at hazardous locations. There are different methods to estimate CMFs, these methods vary from a simple before and after study and before and after study with comparison group to a relatively more complicated methods such EB and FB methods. Also, the cross-sectional method has been commonly used to derive CMFs since it is easier to collect the data compared to before-after methods.

3.1.1 The Simple (Naïve) Before-After Study

This method compares numbers of crashes before and after the treatment is applied. The main assumption of this method is that the number of crashes before the treatment would be expected without the treatment. This method tends to overestimate the effect of the treatment because of the regression to the mean problem (Hauer, 1997).

The naïve before-after approach is the simplest approach. Crash counts in the before period are used to predict the expected crash rate and, consequently, expected crashes had the treatment not been implemented. This basic Naïve approach assumes that there was no change from the ‘before’ to the ‘after’ period that affected the safety of the entity under scrutiny; hence, this approach is unable to account for the passage of time and its effect on other factors such as exposure, maturation, trend and regression-to-the-mean bias. Despite the many drawbacks of the basic Naïve before-after study, it is still quite frequently used in the professional literature because; 1) it is considered as a natural starting point for evaluation, and 2) its easiness of collecting the required data, and 3) its simplicity of calculation. The basic formula for deriving the safety effect of a treatment based on this method is:

$$CMF = \frac{N_a}{N_b} \tag{3-1}$$

where N_a and N_b are the number of crashes at a treated site in the after and before the treatment, respectively. It should be noted that with a simple calculation, the exposure can be taken into account in the Naïve before-after study. The crash rates for both before and after the implementation of a project should be used to estimate the CMFs which can be calculated as:

$$\text{Crash Rate} = \frac{\text{Total Number of Crashes}}{\text{Exposure}} \tag{3-2}$$

where the ‘Exposure’ is usually calculated in million vehicle miles (MVM) of travel, as indicated in Equation (3-3):

$$\text{Exposure} = \frac{\text{Project Section Length in Miles} \times \text{Mean ADT} \times \text{Number of Years} \times 365 \text{ Days}}{1{,}000{,}000} \tag{3-3}$$

Each crash record would typically include the corresponding average daily traffic (ADT). For each site, the mean ADT can be computed by Equation (3-4):

$$\text{Mean ADT} = \frac{\text{Summation of Individual ADTs Associated with each Crash}}{\text{Total Number of Crashes}} \tag{3-4}$$

3.1.2 The Before-After Study with Comparison Group

This method is similar to the simple before and after study, however, it uses a comparison group (CG) of untreated sites to compensate for the external causal factors that could affect the change in the number of crashes. This method also does not account for the regression to the mean as it does not account for the naturally expected reduction in crashes in the after period for sites with high crash rates.

To account for the influence of a variety of external causal factors that change with time, the Before-After with comparison group study can be adopted. A comparison group is a group of control sites that remained untreated, and that are similar to the treated sites in trend of crash history, traffic, geometric and geographic characteristics. The crash data at the comparison group are used to estimate the crashes that would have occurred at the treated entities in the 'after' period had treatment not been applied. This method can provide more accurate estimates of the safety effect than a naïve before-after study, particularly, if the similarity between treated and comparison sites is high. The before-after with comparison group method is based on two main assumptions (Hauer, 1997): 1) The factors that affect safety have changed in the same manner from the 'before' period to 'after' period in both treatment and comparison groups, and 2) These changes in the various factors affect the safety of treatment and comparison groups in the same way. Based on these assumptions, it can be assumed that the change in the number of crashes from the 'before' period to 'after' period at the treated sites, in case of no countermeasures had been implemented, would have been in the same proportion as that for the comparison group. Accordingly, the expected number of crashes for the treated sites that would have occurred in the 'after' period had no improvement applied ($N_{expected,T,A}$) follows (Hauer, 1997):

$$N_{expected,T,A} = N_{observed,T,B} \times \frac{N_{observed,C,A}}{N_{observed,C,B}} \tag{3-5}$$

If the similarity between the comparison and the treated sites in the yearly crash trends is ideal, the variance of $N_{expected,T,A}$ can be estimated from Equation (3-6):

$$Var(N_{expected,T,A}) = N_{expected,T,B}^{2}(1/N_{observed,T,B} + 1/N_{observed,C,B} + 1/N_{observed,C,A}) \tag{3-6}$$

It should be noted that a more precise estimate can be obtained in case of using non-ideal comparison group as explained in Hauer (1997), Equation (3-7):

$$Var(N_{expected,T,A}) = N_{expected,T,B}^{2}(1/N_{observed,T,B} + 1/N_{observed,C,B} + 1/N_{observed,C,A} + Var(\omega)) \tag{3-7}$$

$$\omega = \frac{r_c}{r_t} \tag{3-8}$$

where $$r_c \cong \frac{N_{expected,c,A}}{N_{expected,c,B}} \tag{3-9}$$

and $$r_t \cong \frac{N_{expected,t,A}}{N_{expected,t,B}}$$ (3-10)

And the CMF and its variance can be estimated from Equations (3-11) and (3-12).

$$\text{CMF} = (N_{\text{observed,T,A}}/N_{\text{expected,T,A}})/(1 + (\text{Var}(N_{\text{expected,T,A}})/N_{\text{expected,T,A}}^{2})) \quad (3\text{-}11)$$

$$\text{Var(CMF)} = \frac{\text{CMF}^2[(1/N_{\text{observed,T,A}}) + ((\text{Var}(N_{\text{expected,T,A}})/N_{\text{expected,T,A}}^{2})]}{[1 + (\text{Var}(N_{\text{expected,T,A}})/N_{\text{expected,T,A}}^{2}]^2} \quad (3\text{-}12)$$

Where,

$N_{observed,T,B}$ = the observed number of crashes in the before period for the treatment group.

$N_{observed,T,A}$ = the observed number of crashes in the after period for the treatment group.

$N_{observed,C,B}$ = the observed number of crashes in the before period in the comparison group.

$N_{observed,C,A}$ = the observed number of crashes in the after period in the comparison group.

ω = the ratio of the expected number of crashes in the 'before' and 'after' for the treatment and the comparison group.

r_c = the ratio of the expected crash count for the comparison group.

r_t = the ratio of the expected crash count for the treatment group.

There are two types of comparison groups with respect to the matching ratio: (1) the before-after study with yoked comparison, which involves a one-to-one matching between a treatment site and a comparison site, and (2) a group of comparison sites that is a few times larger than treatment sites. The size of a comparison group in the second type should be at least five times larger than the treatment sites as suggested by Pendleton (1991). Selecting a matching comparison group with similar yearly trend of crash frequencies in the 'before' period could be a daunting task. In this study, a matching of at least 4:1 comparison group to treatment sites was conducted. Identical length of three years of the before and after periods for the treatment and the comparison group was selected.

3.1.3 The Empirical Bayes Before-After Study

The EB method can account for the regression to the mean issue by introducing an estimate for the mean crash frequency of similar untreated sites using SPFs. Since the SPFs use AADT and sometimes other characteristics of the site, these SPFs also account for traffic volume changes, which provides a true safety effect of the treatment (Hauer, 1997).

In the before-after with EB method, the expected crash frequencies at the treatment sites in the 'after' period had the countermeasures not been implemented is estimated more precisely using data from the crash history of a treated site, as well as the information of what is known about the safety of reference sites with similar traffic and physical characteristics. The method is based on three fundamental assumptions (Hauer, 1997):

1. The number of crashes at any site follows a Poisson distribution.
2. The means for a population of systems can be approximated by a Gamma distribution.
3. Changes from year to year from sundry factors are similar for all reference sites.

One of the main advantages of the before-after study with EB is that it accurately accounts for changes in crash frequencies in the 'before' and in the 'after' periods at the treatment sites that may be due to regression-to-the-mean bias. It is also a better approach than the comparison group for accounting for influences of traffic volumes and time trends on safety. The estimate of the expected crashes at treatment sites is based on a weighted average of information from treatment and reference sites as given in (Hauer, 1997):

$$\hat{E}_i = (\gamma_i \times y_i \times n) + (1-\gamma_i)\eta_i \tag{3-13}$$

Where γ_i is a weight factor estimated from the over-dispersion parameter of the negative binomial regression relationship and the expected 'before' period crash frequency for the treatment site as shown in Equation (3-14):

$$\gamma_i = \frac{1}{1 + k \times y_i \times n} \tag{3-14}$$

y_i = Number of average expected crashes of given type per year estimated from the SPF (represents the 'evidence' from the reference sites).

η_i = Observed number of crashes at the treatment site during the 'before' period

n = Number of years in the before period,

k = Over-dispersion parameter

The ‘evidence’ from the reference sites is obtained as output from the SPF. SPF is a regression model which provides an estimate of crash occurrences on a given roadway section. Crash frequency on a roadway section may be estimated using negative binomial regression models (Abdel-Aty and Radwan, 2000; Persaud, 1990), and therefore it is the form of the SPFs for negative binomial model is used to fit the before period crash data of the reference sites with their geometric and traffic parameters. A typical SPF will be of the following form:

$$y_i = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_n)} \tag{3-15}$$

Where βi’s = Regression Parameters,

x_1 and x_2 here are logarithmic values of AADT and section length,

x_i *‘s* $(i > 2)$ = Other traffic and geometric parameters of interest.

Over-dispersion parameter, denoted by k is the parameter which determines how widely the crash frequencies are dispersed around the mean. And the standard deviation (σ_i) for the estimate in Equation (3-16) is given by:

$$\hat{\sigma}_i = \sqrt{(1-\gamma_i) \times \hat{E}_i} \tag{3-16}$$

It should be noted that the estimates obtained from equation 3-10 are the estimates for number of crashes in the before period. Since, it is required to get the estimated number of crashes at the treatment site in the after period; the estimates obtained from equation (3-10) are to be adjusted for traffic volume changes and different before and after periods (Hauer, 1997; Noyce et al., 2006). The adjustment factors for which are given as below:

Adjustment for AADT (ρ_{AADT}):

$$\rho_{AADT} = \frac{AADT_{after}^{\alpha_1}}{AADT_{before}^{\alpha_1}} \tag{3-17}$$

Where, $AADT_{after}$ = AADT in the after period at the treatment site, and

$AADT_{before}$ = AADT in the before period at the treatment site.

α_1 = Regression coefficient of AADT from the SPF.

Adjustment for different before-after periods (ρ_{time}):

$$\rho_{time} = \frac{m}{n} \tag{3-18}$$

Where, m = Number of years in the after period.

n = Number of years in the before period.

Final estimated number of crashes at the treatment location in the after period ($\hat{\pi}_i$) after adjusting for traffic volume changes and different time periods is given by:

$$\hat{\pi}_i = \hat{E}_i \times \rho_{AADT} \times \rho_{time} \tag{3-19}$$

The index of effectiveness (θ_i) of the treatment is given by:

$$\hat{\theta}_i = \frac{\hat{\lambda}_i / \hat{\pi}_i}{1 + \left(\hat{\sigma}_i^{\,2} \middle/ \hat{\pi}_i^{\,2} \right)} \tag{3-20}$$

Where, $\hat{\lambda}_i$ = Observed number of crashes at the treatment site during the after period.

The percentage reduction (τ_i) in crashes of particular type at each site i is given by:

$$\hat{\tau}_i = (1 - \hat{\theta}_i) \times 100\ \% \tag{3-21}$$

The Crash Reduction Factor or the safety effectiveness ($\hat{\theta}$) of the treatment averaged over all sites would be given by (Persaud et al., 2004):

$$\hat{\theta} = \frac{\sum_{i=1}^{m} \hat{\lambda}_i \Big/ \sum_{i=1}^{m} \hat{\pi}_i}{1 + \left(\mathrm{var}(\sum_{i=1}^{m} \hat{\pi}_i) \Big/ (\sum_{i=1}^{m} \hat{\pi}_i)^2 \right)} \tag{3-22}$$

Where, m = total number of treated sites, and

$$\mathrm{var}(\sum_{i=1}^{k} \hat{\pi}_i) = \sum_{i=1}^{k} \rho_{AADT}{}^2 \times \rho_{time}{}^2 \times \mathrm{var}(\hat{E}_i) \quad \text{(Hauer, 1997)} \tag{3-23}$$

The standard deviation ($\hat{\sigma}$) of the overall effectiveness can be estimated using information on the variance of the estimated and observed crashes, which is given by Equation (3-24).

$$\hat{\sigma} = \sqrt{\frac{\theta^2 \left[\left(\mathrm{var}(\sum_{i=1}^{k} \hat{\pi}_i) \Big/ (\sum_{i=1}^{k} \hat{\pi}_i)^2 \right) + \left(\mathrm{var}(\sum_{i=1}^{k} \hat{\lambda}_i) \Big/ (\sum_{i=1}^{k} \hat{\lambda}_i)^2 \right) \right]}{\left[1 + \left(\mathrm{var}(\sum_{i=1}^{k} \hat{\pi}_i) \Big/ (\sum_{i=1}^{k} \hat{\pi}_i)^2 \right) \right]^2}} \tag{3-24}$$

Where, $\mathrm{var}(\sum_{i=1}^{k} \hat{\lambda}_i) = \sum_{i=1}^{k} \lambda_i$ (Hauer, 1997)

Equation (2-16) is used in the analysis to estimate the expected number of crashes in the after period at the treatment sites, and then the values are compared with the observed number of crashes at the treatment sites in the after period to get the percentage reduction in number of crashes resulting from the treatment.

3.1.4 The Full Bayes Before-After Study

The FB is similar to the EB of using a reference population; however, it uses an expected crash frequency and its variance instead of using point estimate, hence, a distribution of likely values is generated.

It is known that the FB approach provided comparable results and might have several advantages over the EB technique as follow: 1) FB models account for the uncertainty associated with parameter estimates and provide exact measures of uncertainty on the posterior distributions of these parameters and hence overcome the maximum likelihood methods' problem of overestimating precision because of ignoring this uncertainty; 2) valid crash models can be estimated using small sample size because of the FB properties, which might be the case of most of road safety benefit analyses; 3) Bayesian inference can effectively avoid the problem of over fitting that occurs when the number of observations is limited and the number of variables is large. In the before-after framework, the FB method integrates the EB two-steps into one by calculating the odds ratio and the SPFs into a single step, and hence, integrating any error or variance of the estimated regression coefficient into the final estimates of the safety effectiveness of a treatment. Most importantly, the flexibility of a FB formulation allows for different model specifications which have the capability of accounting for various levels of correlation. Moreover, Persaud et al., (2009) demonstrated that the FB method is useful approach since it provides more detailed causal inferences and more flexibility in selecting crash count distributions to account for uncertainty in data used. In order to assess crash counts data, several studies utilized the Bayesian Poisson-lognormal model (Park and Lord, 2007; Ma et al., 2008; El-Basyouny and Sayed, 2009). In particular, Ma and Kockelman (2006) adopted a multivariate Poisson-lognormal model to simultaneously analyze crash counts with different injury severity levels through the Bayesian paradigm, providing a systematic approach to estimating correlated count data.

In the Bayesian Poisson-lognormal model, the crash frequency Y_{it} has a Poisson distribution conditional on the σ-field generated by the random variables of unobserved heterogeneity (random errors, ε_t) and the set of independent explanatory variables X_{it} (Munkin and Trivedi, 2002). The model can be set up as follows:

$$Y_{it} \sim \text{Poisson } (\lambda_{it} \text{ for i=1,2,...,m and t=1,2,...,n}) \tag{3-25}$$

which, is the observed crash count at segment *i* in year t with the underlying Poisson mean (i.e., the expected crash frequency) for segment *i* in year t. The Poisson rate is modeled as a function of the log-link using a log-normal distribution:

$$\log\lambda_{it} = \log e_{it} + X'_{it}\beta + \varepsilon_t \tag{3-26}$$

The random effect ε_t is unknown and therefore has its own prior distribution, p(∅). The joint prior distribution is (Gelman et al., 2004)

$$p(\emptyset,\theta) = p(\emptyset)p(\theta|\emptyset), \quad (3\text{-}27)$$

and the joint posterior distribution can be defined as

$$p(\emptyset,\theta|y) \propto p(\emptyset,\theta)p(y|,\emptyset\theta)=p(\emptyset,\theta)p(y|\theta). \quad (3\text{-}28)$$

These posterior distributions were calibrated by Mont Carlo Markov Chain (MCMC) (Gamerman, 2006; Gilks et al, 1996) using all data for the reference sites and the before period data for the treated sites. The CRF (i.e., 1 - CMF) or the safety effectiveness of the treatment averaged over all sites was calculated as follows (Persaud et al., 2009):

$$CRF = 1 - \frac{\sum_{i=1}^{m}\sum_{t=t_Y}^{t_Y+t_Z} Y_{it}}{\sum_{i=1}^{m}\sum_{t=t_Y}^{t_Y+t_Z} \lambda_{it}} \quad (3\text{-}29)$$

Where m is the total number of treated sites, ty is the first year after treatment, t_z is the number of years in the after period, Y_{it} is the actual observed crashes for segment i in year t in the after period, and λ_{it} is the expected crashes without treatment in the after period for segment i in year t.

3.1.5 The Cross-sectional Method

The cross-sectional studies are useful to estimate CMFs where there are insufficient before and after data for a specific treatment that is actually applied. According to NCHRP project 20-7 (Carter et al., 2012), the CMF can be derived by taking the ratio of the average crash frequency of sites with the feature to the average crash frequency of sites without the feature. This method is also known as safety performance functions or crash prediction models which relate crash frequency with roadway characteristics, length and traffic volume of segments.

The cross-sectional studies can be used to estimate the safety effects of certain treatments on specific roadway types (e.g., median width of expressway) since it is difficult to isolate the effect of the treatment from the effects of the other treatments applied at the same time using the before-after methods (Harkey et al., 2008). Moreover, the cross-sectional method is a useful approach to estimate CMFs if there are insufficient crash data before and after a specific treatment that is actually applied. Most cross-sectional studies include principal roadway cross-section attributes such as number of lanes, lane width, shoulder width, surface type, median type, turning lane, vertical grade, and horizontal and vertical curve characteristics, etc. (Shen, 2007). According to the HSM, the CMFs can be estimated by cross-sectional studies when the date of the treatment installation is unknown and the data for the period before treatment installation are not available. The cross-sectional method is generally used for two purposes (Karla and Tarko, 1998): 1) develop predictive model for the expected number of crashes, and 2) quantify safety impact of highway improvements by CMFs. The CMF can be calculated from the coefficient of the variable associated with treatments – e.g., the exponent of the coefficient when the form of the model is log-linear (Lord and Bonneson, 2007) as shown in Equation (3-30).

$$CMF = \exp\{\beta_k \times (x_{kt} - x_{kb})\} \tag{3-30}$$

where,

x_{kt} = Linear predictor *k* of treated sites;

x_{kb} = Linear predictor *k* of untreated sites (baseline condition).

The standard error (SE) of the CMF can be calculated by Equation (3-31) as follows (Harkey et al., 2008):

$$SE = (\exp(\beta_k + SE_{\beta_k}) - \exp(\beta_k - SE_{\beta_k}))/2 \tag{3-31}$$

where,

SE = Standard error of the CMF,

$SE_{\beta k}$ = Standard error of the coefficient β_k,

X_k = Linear predictor *k*.

3.2 Crash Modification Function Development Statistical Approaches

3.2.1 Multivariate Adaptive Regression Splines (MARS)

According to Friedman (1991), the multivariate adaptive regression splines (MARS) analysis can be used to model complex relationships using a series of basis functions (BFs). Abraham et al., (2001) described MARS as a multivariate piecewise regression technique, and the splines can represent the space of predictors broken into number of regions. Piecewise regression, also known as segmented regression, is a useful method when the independent variables, clustered into different groups, exhibit different relationships between the variables in these groups (Snedecor and Cochran, 1980). The independent variable is partitioned into intervals, and a separate line segment is fit to each interval. The MARS divides the space of predictors into multiple knots (i.e., the boundary between regions) and then fits spline functions between these knots (Friedman, 1991). The MARS model is defined as shown in Equation (3-32) (Put et al., 2004).

$$\hat{y} = \exp(b_0 + \sum_{m=1}^{M} b_m B_m(x)) \qquad (3\text{-}32)$$

where,

$\hat{y}$ = predicted response variable,

b_0 = coefficient of the constant basis function,

b_m = coefficient of the m_{th} basis function,

M = number of non-constant basis functions,

$B_m(x)$ = m_{th} basis function.

There are three main steps to fit a MARS model (Put et al., 2004; Haleem et al., 2013). The first step is a constructive phase in which basis functions are introduced in several regions of the predictors using a forward stepwise selection procedure. The predictor and the knot location that contribute significantly to the model are searched and selected in an iterative way in this step. Also, the introduction of an interaction is checked so as to improve the model at the each iteration. The second step (pruning phase) performs backward deletion procedure to eliminate the least contributed basis functions. Generalized cross-validation (GCV) criterion is generally used in this pruning step to find best model. The GCV criterion can be estimated by Equation (3-33). The last step, which is selection phase, selects the optimum MARS model from a group of recommended models based on the fitting results of each (Haleem et al., 2013).

$$GCV(M) = \frac{1}{n}\frac{\sum_{i=1}^{n}(y_i - \hat{y})^2}{(1 - C(M)/n)^2}$$

$$C(M) = M + dM \tag{3-33}$$

where,

y_i = response for observation i,

n = number of observations,

$C(M)$ = complexity penalty function,

d = defined cost for each basis function optimization.

3.2.2 Bayesian Regression

Bayesian analysis is the process of fitting a probability model to a set of data and summarizing the posterior probability distribution on the model parameters and on unobserved quantities. Bayesian methods use the posterior probability to measure uncertainty in inferences based on the statistical analysis. Specifically, Bayesian inference generates a multivariate posterior distribution across all parameters of interest, whereas the traditional statistical approaches offer only the model values of parameters. The advantages of Bayesian estimation methods over classical approaches in both philosophical and practical aspects for transportation applications are well described in Washington et al., (2005).

In Bayesian analysis, MCMC methods (Gilks et al., 1996) using Gibbs sampler are broadly utilized to generate a large number of samples from posterior distribution, since the summary of posterior distributions of model parameters may not be tractable algebraically.

3.2.3 Multiple Linear Regression with Data Mining Technique

Multiple linear regression method was conducted to develop full CMFunction to observe the heterogeneous effects of multiple roadway characteristics among treated sites for the safety effectiveness of treatment using SAS Enterprise Miner program (SAS Institute, Inc., 2014). Figure 3-1 presents processing flow diagram in SAS Enterprise Miner program.

Variable selection node and gradient boosting node with 50 iterations were used to identify correlation among variables and importance of each variable. Variable transformation node was used to identify the variables that need to be transformed. Three different selection criteria options (backward, forward, stepwise) were applied and the best fitted model was found using regression node and model comparison node.

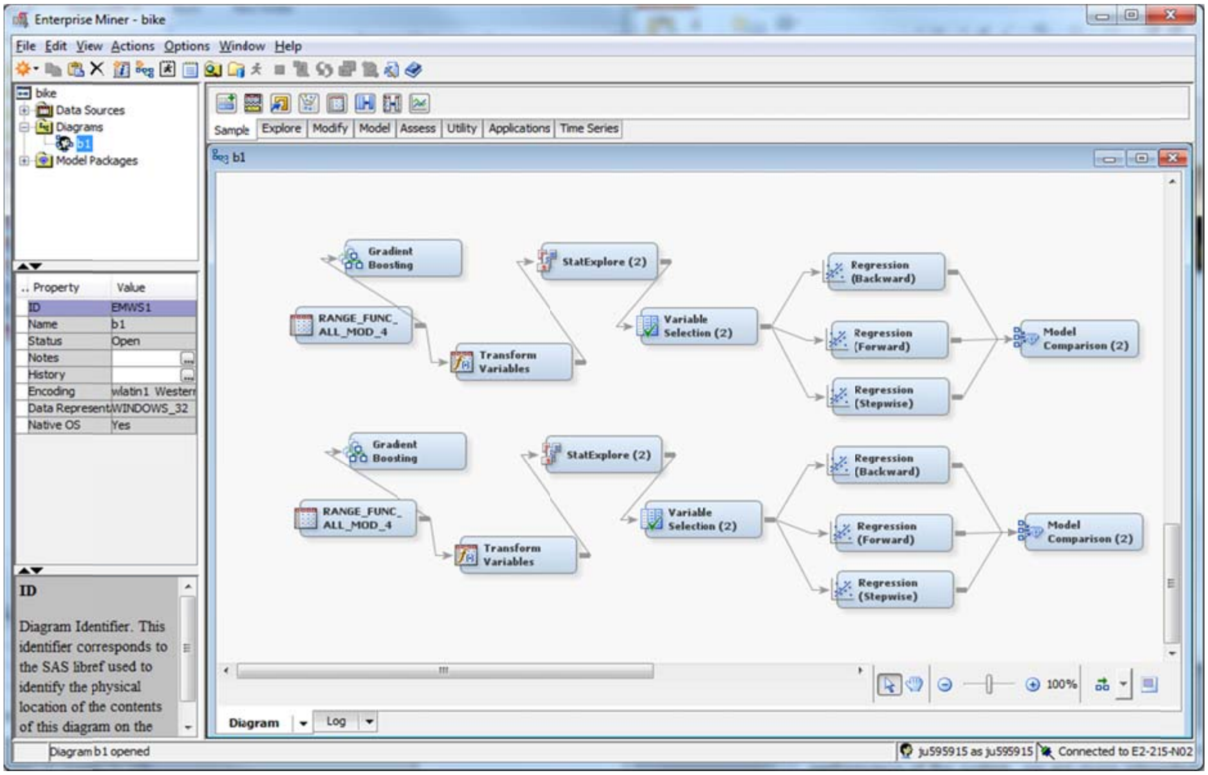


Figure 3-1: Flow Diagram

3.2.4 Generalized Nonlinear Regression Models

To account for nonlinear effects of independent variables, Lao et al., (2013) proposed an application of generalized nonlinear model (GNM) using a nonlinearizing link function to assess safety effects of treatments. The nonlinearizing link function can be described in any functional form including linear, quadratic, log, power, etc. for different values of y (Lee et al., 2015). The functional form of nonlinearizing link function (U(y)) is determined based on the relationship between the logarithm of crash rate and the variable y (Lao et al., 2013). The functional form of GNM is shown in Equation (3-34) as follow:

$$N_{predicted,i} = \exp(\beta_0 + \beta_1 ln(AADT_i) + \beta_k(X_{ki}) + \gamma_l(U(y_{li}))) \tag{3-34}$$

where,

$N_{predicted,\ i}$=Predicted crash frequency on segment i,

β_k = coefficients for the variable k,

$AADT_i$=Annual Average Daily Traffic of segment i (veh/day),

X_{ki} = Linear predictor k of segment i.

γ_l = coefficients for the nonlinear predictor l,

y_{li} = Nonlinear predictor l of segment i.

3.2.5 Autoregressive Moving Average Time Series Model

The Autoregressive Moving Average (ARMA) model consists of the autoregressive (AR) and moving average (MA) models. The model is usually referred to as ARMA (p,q) where p and q represent the possible lags that affect the ARMA model. For instance, the AR (2) model represents that the first and second lags are used to predict the autoregressive relationship for the target time period. The MA (3) model represents the first, second and third lags are used to predict the moving average for the target time period. When these two AR (2) and MA (3) models are combined, the model is referred to as ARMA (2,3). According to the previous studies (Woodward et al., 2011; Box et al., 2013), the ARMA model can be specified as follows:

$$\hat{X}(t) = \phi_1 X(t-1) + \cdots + \phi_p X(t-p) + Z(t) + \theta_1 Z(t-1) + \cdots + \theta_q Z(t-q) + c \quad (3\text{-}35)$$

where,

X=general time series

$\hat{X}(t)$=forecast of the time series Y for time

X(t-1)–X(t-p) = previous P values of time series X.

Z(t)~Z(t-q)= white noise error term

$\phi_1, \dots, \phi_p$=coefficient estimated for autoregressive model

$\theta_1, \dots, \theta_p$= coefficient estimated for moving average model

c=constant

Models can be selected on the basis of the Akaike Information Criterion (AIC) and Schwarz's Bayesian Criterion (SBC). Once ideal time series models are identified, the models can be applied to predict $\hat{X}(t)$ for future time periods.

3.3 Safety Performance Functions

Data from the untreated reference group are used to first estimate a SPF that relates crash frequency of the sites to their traffic and geometrical characteristics. Generally, a SPF is a crash prediction model, which relates the frequency of crashes to traffic (e.g., AADT) and the roadway characteristics (e.g., number of lanes, width of lanes, width of shoulder, etc.). There are two main types of SPFs in the literature: (1) full SPFs and (2) simple SPFs. Full SPF is a mathematical relationship that relates both traffic parameters and geometric parameters as explanatory variables, whereas simple SPF includes AADT as the sole explanatory variable in predicting crash frequency on a roadway entity. It is worth mentioning that the calibrated CMFs in the HSM are based only on the simple 'SPF'.

3.3.1 Negative Binomial Models

Crash data have a gamma-distributed mean for a population of systems, allowing the variance of the crash data to be more than its mean (Shen, 2007). Suppose that the count of crashes on a roadway section is Poisson distributed with a mean λ, which itself is a random variable and is gamma distributed, then the distribution of frequency of crashes in a population of roadway sections follows a negative binomial probability distribution (Hauer, 1997).

$y_i|\lambda_i \approx$ Poisson (λ_i)

$\lambda \approx$ Gamma (a,b)

Then, P(y_i) ≈ Negbin (λ_i, k)

$$= \frac{\Gamma(1/k + y_i)}{y_i!\Gamma(1/k)} \left(\frac{k\lambda_i}{1 + k\lambda_i}\right)^{y_i} \left(\frac{1}{1 + k\lambda_i}\right)^{1/k} \tag{3-36}$$

where,

y = number of crashes on a roadway section per period;

λ = expected number of crashes per period on the roadway section;

k= over-dispersion parameter.

The expected number of crashes on a given roadway section per period can be estimated by Equation 3-37.

$$\lambda = \exp(\beta^T X + \varepsilon) \tag{3-37}$$

where,

β = a vector of regression of parameter estimates;

X= a vector of explanatory variables;

exp(ε) = a gamma distributed error term with mean one and variance k.

Because of the error term the variance is not equal to the mean, and is given by Equation 3-38.

$$\mathrm{var}(y) = \lambda + k\lambda^2 \tag{3-38}$$

As $k \rightarrow 0$, the negative binomial distribution approaches Poisson distribution with mean λ. The parameter estimates of the binomial regression model and the dispersion parameter are estimated by maximizing the likelihood function given in Equation 3-39.

$$l(\beta, k) = \prod_i \frac{\Gamma(1/k + y_i)}{y_i!\,\Gamma(1/k)} \left(\frac{k\lambda_i}{1 + k\lambda_i}\right)^{y_i} \left(\frac{1}{1 + k\lambda_i}\right)^{1/k} \tag{3-39}$$

Using the above methodology negative binomial regression models were developed and were used to estimate the number of crashes at the treated sites.

CHAPTER 4. DATA COLLECTION AND PREPARATION

4.1 Introduction

To adopt before-after studies and cross-sectional method to estimate CMFs, intensive data collection has to be performed and sufficient treated sites with enough crash frequency are needed. For example, the observational before-after with EB method requires having 30-50 locations with a total of 100 crashes per year for calibration purposes. Moreover, as mentioned in phase I, the HSM procedure needs very detailed roadway characteristics data to estimate calibration factors for each category and its subcategory.

Similar to data collection procedure in phase I, multiple data sources that are maintained by FDOT were considered for investigation and determination of the most complete and accurate procedure. These data sources include Financial Management (FM) Database, the roadway characteristic inventory (RCI), Crash Analysis Reporting System (CARS), FDOT GIS (Geographic Information System) layers, and the Transtat I-view aerial mapping system. To verify the accuracy of data, Google Earth and Google street view were considered. This data collection effort is needed for various data issues such as availability of specific geometric characteristics, easiness of accessing and obtaining information, completeness and accuracy of the data, and time needed for download and preparation. The extensive data collection and preparation process are as below:

1. Identification of treatment and treated sites
    - Literature review (e.g., HSM, related research papers, reports, etc.)

- FM Database
- RCI data comparison
- Field research
- Survey

2. Obtainment of data from multiple sources

- Roadway characteristics
    - RCI, FDOT GIS Layer, Google Earth, Google Street View
- Crash data
    - CARS, Signal Four Analytics
- Before and after time periods
    - FM Database, RCI data comparison, Google Earth historical map, Google Street View historical images

3. Verification of data accuracy

- Location of identified treated and reference sites
    - Transtat I-view, ArcGIS, Video Log Viewer Application
- Roadway characteristic data accuracy
    - Google Earth, Google Street View, Video Log Viewer Application

4.2 Reported Data Sources in Phase I

4.2.1 Financial Management (FM) Database

Road facility construction projects are recorded in the FM Database. The FM offers a search system named Financial Project Search (FPS) and through this system, specific financial project and its relevant information can be identified. Also, the system provides a function to search financial projects by various conditions such as district, status, work types, and year. The information provided in the FM was too general in which other data sources have to be utilized to collect more information about the treated sites.

4.2.2 Roadway Characteristics Inventory (RCI)

RCI is mainly used to identify the type of road configuration and geometrics of roadway segments and intersections, e.g., overall surface lane width, number of lanes, shoulder type and width, median width, maximum speed limit, and other roadway and traffic characteristics.

4.2.3 Crash Analysis Resource System (CARS)

CARS is maintained by FDOT. It consists of the traffic crash data from 2003 to date. The data can be retrieved from the server with detailed crash information. This database was generated by collecting data from the Department of Highway Safety and Motor Vehicles (DHSMV).

4.2.4 Transtat-Iview Aerial Mapping System

Transtat-Iview is a geographical database system provided by FDOT TranStat Department that is considered a good source to verify information collected from the FM. It provides a location with beginning and end mileposts for an identified treated site. Although the treated site can be specified in the Transtat-Iview, it does not provide detailed historical geometry about the site. Therefore, Google Earth was used as an additional source to verify data collected from the FM.

4.2.5 Google Earth

Google Earth provides historical satellite imagery layers for different years. This feature enabled us to compare the before and after geometrical characteristics more precisely. Although that Google Earth provided valuable information and helped to identify various problems in the FM database, this process could be extremely tedious and time consuming.

4.2.6 Video Log Viewer Application

Video Log Viewer Application was also used to check the validity and accuracy of the collected data. However, since the data for some sites are not completed, Google Earth is mostly used for verification of data.

4.3 Additional Data Sources in Phases II

4.3.1 Signal Four Analytics

Signal Four Analytics is a web based geographic system providing up-to-date crash data with flexibility querying criteria. Users could define their own buffer range along with specific settings to query data. After the data was queried, Signal Four Analytics also provides the function to export the crash list with latitude-longitude grid, as well as excel sheet. One point worth mentioning, the annual crash counts in Signal Four Analytics are not stable. The crash counts have risen significantly from 2013, due to changes in the reporting system. The after period includes more PDO crashes than the before period. Due to this inconsistency, it is not suitable to perform before and after studies using crash data in Signal Four Analytics. On the other hand, this database provides advantages in performing cross-sectional method. If we perform the cross-sectional method using data after 2013 with more complete PDO crashes, we will be able to detect treatments' performance especially for non-injury crashes. Other disadvantages of Signal 4 Analytics is that it is not available for the whole state before 2010 which prohibit using it for before/after studies. It also defines injury crashes at one level, instead of levels 2-4 as in CARS.

Figure 4-1 is the interface of Signal Four Analytics. Left panel shows the number of crashes happen within the current searching criteria. Right panel is the place which allow users to set specific searching criteria. At the mid-bottom, the list of crashes are presented with crash reporting number, crash reporting agency, crash types and other important informations.

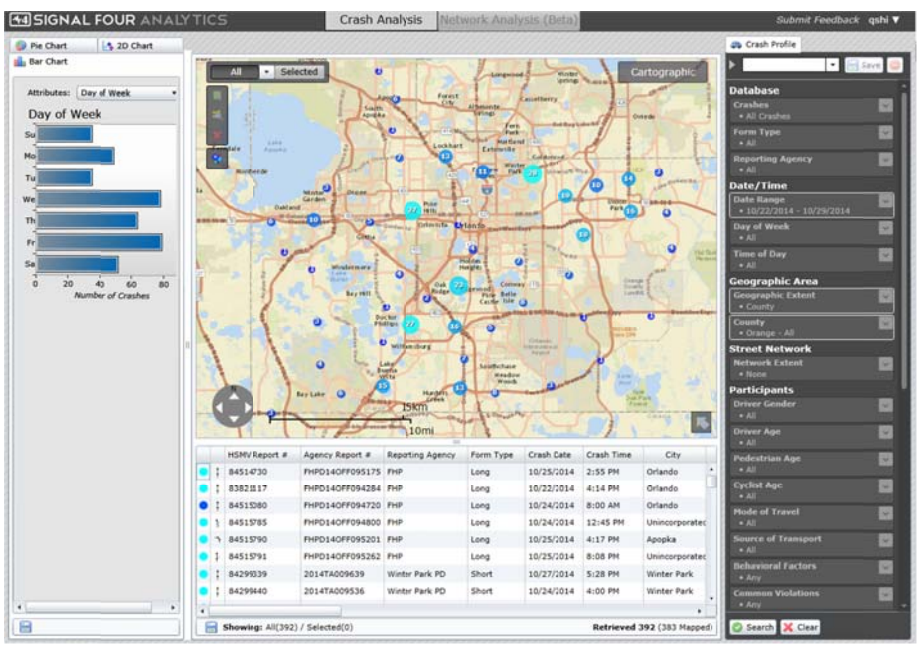


Figure 4-1: Screenshot from Signal Four Analytics System

4.3.2 ArcGIS

ArcGIS is a geographic database system that helps researchers and engineers to query and organize data using map based environment. Using the base map and contour map provided by Transportation Statistics Office under Florida Department of Transportation. Our team is able to locate roadway features such as lane width and location of signal head from the layer file provided by FDOT (http://www.dot.state.fl.us/planning/statistics/gis/). Besides, after we prepared and managed the crash data from Signal for Analytics and CARS, we were able to import the crashes into the ArcGIS system. In this case, querying data is much efficient after implement ArcGIS. In addition, linking ArcGIS with Google Earth based on latitude and longitude makes treatment identification less time consuming. In phase II, we successfully associated ArcGIS with Transtat I-view, Google Earth and Google Street View historical images. Under this setting, we could save time in data collection, using this efficient way of data collection. We can estimate new treatments and re-estimates the treatment in Phase I with greater samples.

The screen shot, as shown in Figure 4-2, presents the crashes and intersections in the state of Florida. The blue contour is the base route provided by FDOT, and the signal legends are the location of traffic signals. Besides the green dots are the location where traffic crashes occurred from 2008 to 2012.

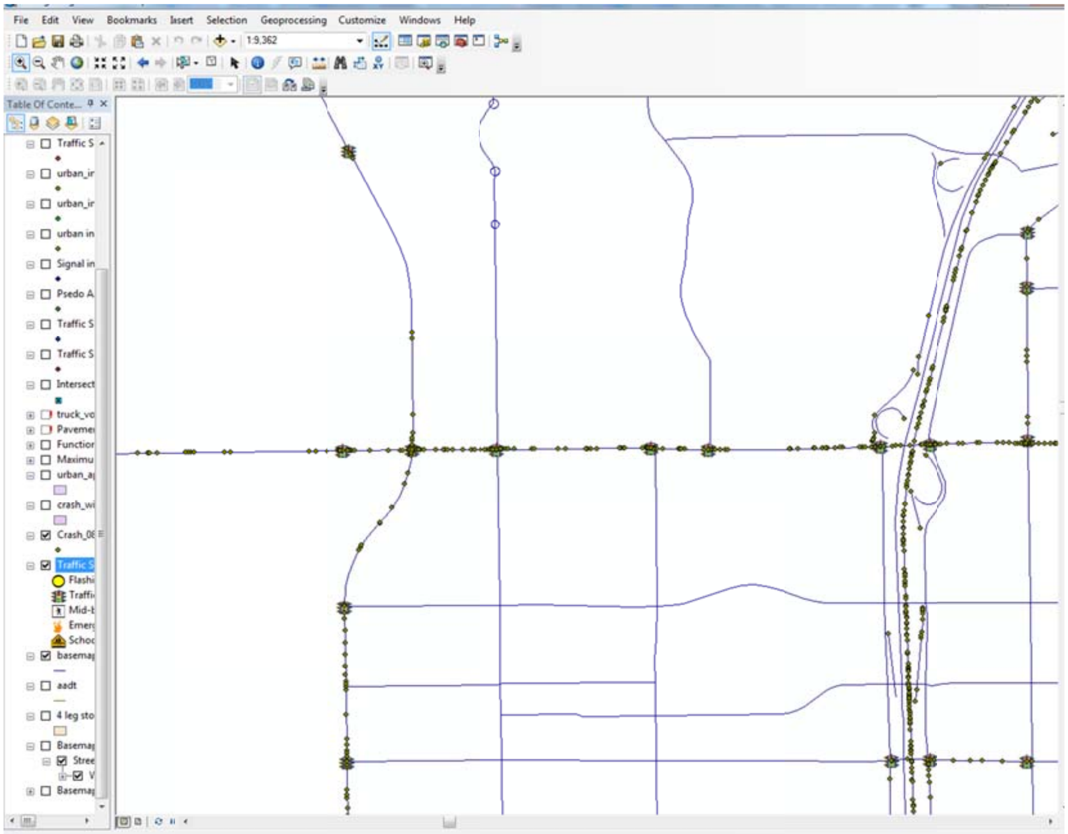


Figure 4-2: Screenshot from ArcGIS

4.3.3 Google Street View Historical Images

Google have started to provide historical images for street view since mid-2014. This is a useful feature for us to identify treatments. For example, we used to identify treatments in Google Earth to search for historical data. However, it is almost impossible to identify treatments such as installing reflectorized signal plates from the satellite map. Figure 4-3 and 4-4 represent the before and after reflectorized signal plates was installed. Comparing these two images, we would be able to identify the reflectorized signal plates for this desired location.

Figure 4-3: Screenshot from Google Street View in May 2008

Figure 4-4: Screenshot from Google Street View in May 2011 (Adding Reflectorized Signal Back Plate)

4.3.4 Survey

In phase I, we validated CMFs for 17 treatments in Florida with HSM Part D. We referenced the results of previous studies and the FPS to determine the selection of treatment target in Phase I. Our intention is to analyze the important treatments in the State of Florida because some of these treatments might not be available or reliable. In fact, after we performed cross comparison between FPS and RCI, we discovered that there is actually missing treatments in FPS. As we raised this issue in Phase I, we realized that only state level projects will be included in the FPS. Understanding this, we may lose some important local treatments that are omitted in FPS. Therefore, a survey is prepared as an added method to identify the common treatments in Florida. In addition to FPS and the treatments included in the HSM CMF chapters, getting input from practitioners in Florida can help us tailor some of our work to their needs.

In this survey, we separate the treatments into two major types “intersection” and “roadway segment”. For intersections, 46 treatments are addressed. On the other hand, 27 roadway segment related treatments are exhibited in the survey.

We distributed this survey to counties and district transportation offices and have collected 14 responses by the end of Oct 30th 2014. Among these 14 effective survey results, 7 of them are from county engineers while another half of them are from district engineers. We are trying to collect more responses from the distributed survey as another way to determine the common treatment types. Based on the collected surveys, we determine the treatments with higher acceptance rates that are considered as common implementations throughout the State of Florida. As it shown in Table 4-1, although some treatments are considered as common treatments in counties and districts, data is not available to retrieve from the FMS or county/district office. These treatments will have higher priorities if data is available. The form of survey is presented in Appendix A.

In Table 4-1, five of the most common treatments for intersections are listed. Among these five treatments, we have covered two treatments which are providing left turn lanes at 3-leg and 4-leg intersections in phase I. Besides, the reflectorized signal plates will be addressed in phase II. The other two treatments are related to pedestrian safety. We understand that pedestrian safety is extremely important in Florida due to high pedestrian volume. However, estimating the safety effects of installing pedestrian signals or count down signals is relatively difficult. This is due to the data availability of pedestrian volume.

In the segment part, eight treatments are displayed based on the survey completed by county/district engineers. Five treatments were estimated out of the top eight popular treatments in phase I. Among these five treatments, two of them will be refined in phase II using improved data and methods. On top of these five treatments, we are going to cover two new treatments which are adding guardrails and road resurfacing in phase II. Overall, we will cover seven treatments out of the top eight treatments in the final report.

Table 4-1: Result of Treatment Survey by County/District Engineers

Intersection				
Treatment Type	Accept Rate	Phase I	Phase II	Considering
Provide a left-turn lane on one or more approaches to three-leg intersections	0.93	X		
Install pedestrian signal heads at signalized intersections	0.93			X
Install reflectorized signal plates at signalized intersections	0.93		X	
Provide a left-turn lane on one or more approaches to four-leg Intersections	1	X		
Install pedestrian countdown signals	1			X
Segment				
Treatment Type	Accept Rate	Phase I	Phase II	Considering
Add street light	0.71	X		
Add bike lanes	0.71	X		
Add shoulder rumble strips on rural highways	0.79	X	X	
Widen shoulder width on rural highways	0.79	X	X	
Add guardrails on roadside	0.79		X	
Remove roadside fixed objects	0.79			X
Add raised median	0.86	X		
Resurface roadways	1		X	

4.4 Data Collection and Preparation for New Treatments in Phase II

4.4.1 Adding Shoulder Rumble Strips; Widening Shoulder Width; Adding Shoulder Rumble Strips + Widening Shoulder Width on Rural Two-lane Roadways

The road geometry data for roadway segments were identified for 8 years (2004-2011), and for consistency of all treated sites, crash records were collected for 2 years (2004-2005) for before period and 2 years (2010-2011) for after period from RCI and CARS databases. The three types of treatments, which are adding shoulder rumble strips (SRS), widening (1ft ~ 9ft) shoulder width (WSW) and combination of two treatments (SRS+WSW), were identified from the RCI roadway segments data for locations which have been treated in the years between 2006 and

2009 to ensure sufficient sample size. The total lengths of treated rural two-lane segments for SRS, WSW, and SRS+WSW were 61.274, 180.259, and 30.465 miles long, respectively. The total numbers of treated segments for SRS, WSW, and SRS+WSW were 70, 243, and 68, respectively. Also, the reference sites that have similar roadway characteristics to the treated sites in the before period were identified using the RCI database. A total of 2745 roadway segments with 1915.451 miles in length were identified as reference sites. Moreover, all crash types and single vehicle run-off roadways (SVROR) crashes were used for analysis. Distributions of each variable among these treated segments are summarized in Table 4-2.

Table 4-2: Descriptive Statistics of the Variables for Treated Sites

(a) Shoulder Rumble Strips (SRS)

	Crash frequency in before period				Crash frequency in after period			
Variable	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Number of All (KABCO) crashes	3.686	6.502	0	31	2.814	5.234	0	28
Number of All (KABC) crashes	3.529	6.152	0	29	2.543	4.784	0	26
Number of SVROR (KABCO) crashes	0.929	1.697	0	8	0.600	1.082	0	5
Number of SVROR (KABC) crashes	0.814	1.582	0	8	0.500	0.913	0	4

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day) in before period	6901	4326	2286	19100
AADT (veh/day) in after period	7246	4121	3086	18500
Length (mile)	0.875	1.132	0.107	4.904
Surface width (ft)	24	0.341	22	26
Maximum speed limit (mph)	56.5	4.842	35	60
Original shoulder width	2ft = 6sites, 4ft = 19sites, 6ft = 24sites, 8ft = 7sites, 10ft = 7sites, 12ft = 7sites			

(b) Widening Shoulder Width (WSW)

	Crash frequency in before period				Crash frequency in after period			
Variable	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Number of All (KABCO) crashes	2.414	5.035	0	31	1.729	3.878	0	24
Number of All (KABC) crashes	2.157	4.732	0	29	1.529	3.622	0	23
Number of SVROR (KABCO) crashes	0.429	1.303	0	9	0.257	0.695	0	4
Number of SVROR (KABC) crashes	0.357	1.155	0	8	0.200	0.628	0	4

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day) in before period	5896	3882	1200	17500
AADT (veh/day) in after period	6140	4258	1600	18500
Length (mile)	0.673	0.907	0. 130	4.240
Surface width (ft)	23.771	0.935	18	24
Maximum speed limit (mph)	48.929	7.889	30	60
Original shoulder width	2ft = 9sites, 4ft = 8sites, 6ft = 33sites, 8ft = 43sites, 10ft = 96sites, 12ft = 54sites			

(c) Shoulder Rumble Strips + Widening Shoulder Width (SRS+WSW)

	Crash frequency in before period				Crash frequency in after period			
Variable	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Number of All (KABCO) crashes	1.882	2.657	0	11	1.235	1.838	0	10
Number of All (KABC) crashes	1.750	2.588	0	11	1.088	1.646	0	9
Number of SVROR (KABCO) crashes	0.529	0.872	0	4	0.294	0.459	0	1
Number of SVROR (KABC) crashes	0.441	0.780	0	3	0.221	0.418	0	1

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day) in before period	7566	5350	1650	23500
AADT (veh/day) in after period	7145	5308	1350	25000
Length (mile)	0.448	0.744	0.120	4.690
Surface width (ft)	23.882	1.420	20	32
Maximum speed limit (mph)	53.529	10.653	30	65
Original shoulder width	2ft = 7sites, 4ft = 8sites, 6ft = 6sites, 8ft = 12sites, 10ft = 7sites, 12ft = 28sites			

4.4.2 Increasing Lane Width; Increasing Shoulder Width at Straight and Curved Rural Two-lane Roadways

Five years (2008-2012) of crash data and traffic and roadway characteristics data were obtained from CARS and RCI historical database. Both data sets are maintained by FDOT. In this study, each roadway segment has uniform geometric characteristics in before and after periods except changes of AADT. A segment is represented by roadway identification numbers and beginning and end mile points. AADT in 2010 was used as an average AADT in 2008-2012. Roadway characteristics data from RCI system for the target segments were matched with crash data by roadway ID and segment mile point for each segment. A total of 2816 rural two-lane roadway segments with 3791.574 miles in length were identified for the analysis. Table 4-3 presents the descriptive statistics of the parameters for the target segments.

Table 4-3: Descriptive Statistics of the Variables for Target Sites

Variable	Mean	S.D.	Min.	Max.
Number of crashes				
Number of KABCO crashes	3.831	7.886	0	81
Number of KABC crashes	2.209	4.612	0	44
Number of KAB crashes	1.502	3.216	0	31
Traffic and roadway geometric characteristics				
AADT (veh/day)	4484.485	3551.692	1004	36000
Length (mile)	1.346	1.492	0.101	5.099
Lane width (ft)	11.698	0.742	9	15
Shoulder width (ft)	6.354	3.138	1	16
Maximum speed limit (mph)	50.844	8.432	25	60
Horizontal curve (1: curved section, 0: non-curved section)	Curved segments: 156 sites, Straight segment: 2660 sites			
Shoulder type (1: paved, 0: others (lawn, gravel, marl, gutter, etc.))	Paved shoulder: 1749 sites, Non-paved shoulder: 1067			

4.4.3 Installation of Median Barriers on Rural Multilane Roadways

According to the HSM, the Install median barriers on rural multilane roadways treatment is safety effective in reducing all types of crashes by 30% and 43% for injury (KABC) and fatal (K) severities, respectively. For the Install median barriers on rural multilane roadways treatment, the traffic and roadway geometric characteristics data for 3 years (2010-2012) was obtained from the RCI historical database. The data for rural multilane roadways were collected where roadway geometric conditions of each segment have not been changed during the 3-year period. The roadway segments with median barriers were determined based on the roadway ID, beginning mile post, end mile post, roadway functional class (FUNCLASS), and median type (RDMEDIAN) in the RCI data.

Table 4-4 shows the number of roadway segments and total length of treated and reference sites. The range of AADT is specified in the description. Table 4-5 presents descriptive statistics of collected roadway and traffic parameters.

Table 4-4: Number of Roadway Segments and Length of Treated and Reference Sites

Treated Sites		Reference Sites	
Number of Segments	Total Length	Number of Segments	Total Length
129	141.806 mile	305	366.582 mile
AADT: 5,000~48,000			

Table 4-5: Descriptive Statistics of the Variables

Variable Name	Definition	Mean	S.D.	Min.	Max.
AADT	Annual Average Daily Traffic (veh/day)	26,739.03	5,708.01	20,000	39,500
Length	Roadway Segment Length (mile)	1.17	1.51	0.101	9.576
Shld_Width	Width of shoulder lane (ft)	8.47	2.50	2	12
Med_Width	Width of median (ft)	61.42	32.27	14	250
Max_Speed	Maximum Speed Limit (mph)	66.39	7.14	35	70
Lane_width	Width of vehicle travel lane (ft)	12.01	0.13	11.5	13
No_Lanes	Number of lanes in one direction	2.06	0.24	2	3

In order to calculate the safety effects for the Install median barriers on rural multilane roadways treatment using the cross-sectional method, crash records for 5 years (2008-2012) from CARS database were obtained. The collected crash records were matched with the target sites data based on roadway ID and milepost of each segment. Table 4-6 presents the distributions of each crash type.

Table 4-6: Descriptive Statistics of Crash Records

Crash type	Severity	Mean	S.D.	Min.	Max.
All crashes	KABCO	17.537	23.170	0	178
	KABC	9.327	11.864	0	78
	KAB	5.929	7.577	0	51
	KA	2.618	3.470	0	24
ROR crashes	KABCO	5.083	8.312	0	87
	KABC	2.956	4.503	0	31
	KAB	1.802	2.790	0	20
	KA	0.742	1.352	0	13

4.4.4 Increasing the Distance to Roadside Poles and Trees; Decreasing Density of Driveways and Roadside Poles on Rural Multilane Roadways

The roadside countermeasures have been known as one of the most important treatments for roadway safety to reduce injury crashes. Road geometry and traffic data for roadway segments were identified for 5 years (2008-2012) from the RCI historical database, respectively. According to the HSM, for the application of cross-sectional method, it is recommended that crash prediction models are developed using the crash data for both treated and untreated sites for the same time period – typically 3-5 years.

Although the RCI database provide more than 200 roadway characteristics for a specific roadway segment in a given date, it does not have information of more detailed roadside features such as number of utility poles, number of signs, number of isolated trees or groups, number of driveways, distance to poles, distance to signs, distance to trees, etc. Therefore, extensive effort by the research team was needed to use Google Earth and Street-view applications to identify these roadside elements. The Google Earth and Street-view applications have recently started to provide historical images and surrounding views from 2007 to recent. In this study, each roadway segment has uniform geometric characteristics for five years except AADT. Also, AADT in 2010 was used as an average AADT for the period 2008–2012. The undivided rural multilane roadway segments were determined based on the roadway ID, beginning mile post, end mile post, roadway functional class (FUNCLASS), and median type (RDMEDIAN) in the RCI data. A total of 222 rural undivided multilane roadway segments with 81.758 miles in length were identified as target sites. Table 4-7 presents descriptive statistics of collected roadway and traffic parameters.

Table 4-7: Descriptive Statistics of the Variables

Variable Name	Definition	Mean	S.D.	Min.	Max.
Variables related to traffic and basic roadway geometric characteristics					
AADT	Annual Average Daily Traffic (veh/day)	14,654.60	8,650.73	1,500	34,500
Length	Roadway Segment Length (mile)	0.368	0.427	0.1	3.0
Lane_width	Width of vehicle travel lane (ft)	11.243	0.956	9.5	15
Max_Speed	Maximum Speed Limit (mph)	34.82	4.8	25	55
Hrz_Curve	One or more curved sections in the segment = 28sites, No curve = 194sites				
Variables related to roadside characteristics					
Shld_Width	Width of shoulder lane (ft)	3.45	2.24	1.5	10
Dist_Poles	Average Distance to Poles (ft)	3.752	2.378	0.5	19.5
Dist_Trees	Average Distance to Trees (ft)	12.265	7.245	0	58.0
Den_Poles	Density of Poles (per mile)	52.910	21.793	2.333	113.208
Den_Trees	Density of Trees (per mile)	31.765	20.267	0	125.0
Den_Drivwy	Density of Driveways (per mile)	28.306	14.993	0	76.749

Crash records were collected for 5 years (2008-2012) from CARS database. The obtained crash records were matched with the target sites data based on roadway ID and milepost of each segment. Distributions of each crash type are summarized in Table 4-8.

Table 4-8: Descriptive Statistics of Crash Records

Crash types (Severity)	Mean	S.D.	Min.	Max.
All (KABCO)	3.027	5.856	0	37
All (KABC)	1.270	2.342	0	19
All (KAB)	0.635	1.413	0	15
ROR (KABCO)	0.257	1.134	0	15

4.4.5 Decreasing School Zone Speed Limits on Segments in School Zone Area on Rural + Urban Roadways

In the HSM, the safety performance of changing speed limits in school zones has not been quantified. However, the HSM suggests the Changing speed limits in school zones on urban arterials treatment as a possible countermeasure to investigate its safety impact.

For the changing school zone speed limits in school zone area on rural and urban roadways treatment, the traffic and roadway geometric characteristics data for 3 years (2010-2012) was obtained from the RCI historical database, respectively. The data for both rural and urban roadways were collected where roadway geometric conditions of each segment have not been changed during the 3-year period. The roadway segments in school zones were determined based on the roadway ID, beginning mile post, end mile post, roadway functional class (FUNCLASS), and school zone speed limit (SCHLSPED) in the RCI data.

Table 4-9 shows the number of roadway segments and total length of target sites. The range of AADT is specified in the description. Table 4-10 presents descriptive statistics of collected roadway and traffic parameters.

Table 4-9: Number of Roadway Segments and Length of Target Sites

Speed Limits in School Zone (mph)	Total Length (mile)	Number of Sites
15	7.519	107
20	17.458	148
25	1.331	16
30	2.556	12
35 ≦	0.857	5
AADT: 1,500~50,000		

Table 4-10: Descriptive Statistics of the Variables

Variable Name	Definition	Mean	S.D.	Min.	Max.
AADT	Annual Average Daily Traffic (veh/day)	13,874.01	10,496.22	1,500	50,000
Length	Roadway Segment Length (mile)	0.1	0.09	0.007	0.485
Shld_Width	Width of shoulder lane (ft)	4.07	2.29	1.5	12
Road_type	1= Divided, 0= Undivided	1= 183 sites, 0= 105 sites			
Max_Speed	Maximum Speed Limit (mph)	40.24	6.94	25	65
SCH_Speed	School Zone Speed Limit (mph)	19.17	4.53	15	40
Lane_width	Width of vehicle travel lane (ft)	11.96	0.79	10	16
No_Lanes	Number of lanes in one direction	1.89	0.64	1	4

In order to estimate CMF for the changing school zone speed limits in school zone area on rural and urban roadways treatment using the cross-sectional method, crash records from CARS database were collected for 5 years (2008-2012). The obtained crash records were matched with the target sites data based on roadway ID and milepost of each segment. Descriptive statistics of crash records are presented in Table 4-11 based on each crash type.

Table 4-11: Descriptive Statistics of Crash Records

Crash types (Severity)	Mean	S.D.	Min.	Max.
All (KABCO)	3.726	7.975	0	67
All (KABC)	2.035	4.435	0	32
All (KAB)	1.149	2.564	0	22
Bike (KABCO)	0.087	0.317	0	2
Pedestrian (KABCO)	0.087	0.377	0	3

4.4.6 Increasing Shoulder Width, Changing School Zone Speed Limits, Installation of Flashing Beacon at School Zone Signs, Decreasing Number of Driveways on Segments in School Zone Area on Urban Arterials

The road geometry data for school zone areas on urban arterials were identified for 7 years (2007-2013) and crash records were also collected for 7 years (2007-2013) from multiple sources maintained by the FDOT. These include the RCI and CARS database. A segment is represented by roadway identification numbers and beginning and end mile points. Roadway characteristics data from RCI system for the target segments were matched with crash data by roadway ID and segment mile point for each segment. For the analysis, only the crashes occurred during school zone operation time in school zone areas were identified. Although the RCI database provide more than 200 roadway characteristics for a specific roadway segment in a given date, it does not have information of more detailed roadside features such as number of intersections, number of driveways, number of signs, installation of flashing beacons, number of crosswalks, etc. Therefore, extensive effort by the research team was needed to use Google Earth and Street-view applications to identify those additional roadway cross-section elements. A total of 209 urban school zone areas with 36.902 miles in length were identified for the analysis. For the application of cross-sectional method, it is recommended in the HSM that crash prediction models are developed using the crash data for both treated and untreated sites for the same time period. The descriptive statistics of the parameters for the treated sites are presented in Table 4-12.

Table 4-12: Descriptive Statistics of the Variables

Variable		Mean	S.D.	Min.	Max.
Number of crashes					
Total (all types) crashes	KABCO	2.635	4.161	0	36
	KABC	1.192	1.824	0	11
	KAB	0.548	0.967	0	6
Heavy vehicle related crashes	KABCO	1.207	1.860	0	10
	KABC	0.471	0.839	0	4
	KAB	0.221	0.547	0	3
Rear-end crashes	KABCO	0.841	2.040	0	22
	KABC	0.404	0.988	0	7
Non-motorized (pedestrian related + bike related) crashes	KABCO	0.226	0.689	0	5
Traffic and roadway geometric characteristics					
AADT (veh/day)		14104.976	10140.530	1500	49000
Length (mile)		0.177	0.082	0.030	0.397
School zone speed limit (mph)		19.303	4.436	15	35
Number of driveways		2.058	1.960	0	14
Number of intersections		0.327	0.510	0	2
Number of crosswalks		1.135	0.799	0	4
Number of lanes		1.904	0.681	1	4
Surface width (ft)		22.635	7.888	10	50
Shoulder width (ft)		3.909	2.280	1	12
Median width (ft)		10.77	10.31	0	53
Crosswalk rate (crosswalks/(driveways+intersections))		0.304	0.309	0	2.000
Median exist binary parameter		1: school zone with median (45 sites), 0: no median (164 sites)			
School zone speed limit binary parameter		1: school zone speed limit less than or equal to 20 mph (185 sites), 0: others (24 sites)			
Bike lane binary parameter		1: bike lane (17 sites), 0: no bike lane (192 sites)			
Sidewalk binary parameter		1: sidewalk (178 sites), 0: no sidewalk (31 sites)			
Flashing beacon binary parameter		1: flashing beacon (182 sites), 0: no flashing beacon (27 sites)			

4.4.7 Widening Urban 4- to 6-lane Arterials

For the evaluation of safety effects of widening urban 4- to 6-lane roadways treatment, three sets of data for Florida from FDOT were used: RCI data for ten years (2003-2012), financial project information, and crash data for ten years (2003-2012). The RCI database provides current and historical roadway characteristics data and reflects the features of specific segments for selected dates. The Financial Management System provides detailed information on a specific financial project such as district number, status, work type, costs, period, and year. The treated sites with urban four-lane roadways widened to six-lanes were identified using these two databases. The total length of the treated urban arterials was 46.908 miles long, and the total number of the treated segments was 138. Also, the reference sites that have similar roadway characteristics to the treated sites in the before period were identified using the RCI database. In order to obtain the reference sites, untreated roadway segments under the same roadway ID as a treated segment were identified since segments in one roadway ID mostly have similar roadway characteristics (e.g., AADT, number of lanes, lane width, etc.). If all segments for one roadway ID have been treated, the reference sites that have similar roadway characteristics as the treated roadway within the same city or county level were selected. A total of 177 roadway segments with 125.432 mile in length were identified as reference sites. Moreover, any missing values or errors of data were verified and corrected or removed using Transtat-Iview (a GIS searching system offered by FDOT) and Google Earth.

The crash data were obtained from the CARS for these treated and reference sites in before and after periods. All segments that have been treated in the years between 2006 and 2008 were selected for analysis to ensure sufficient sample size. The crash data was extracted for each site for the 3-year before period (2003-2005) and the 4-year after period (2009-2012). Roadway characteristics data from the RCI system for the treated and reference sites were matched with crash data by roadway ID and segment mile point for each site.

The descriptive statistics of the parameters for the treated sites are presented in Table 4-13. It is worth mentioning that shoulder width and median width were narrower after treatment for 17.14% and 40.00% of treated sites, respectively. This may have been because of right of way restriction for widening roadways as in many cases of urban areas. To consider AADT changes before and after the treatment in terms of operational performance, the treated sites were grouped into 3 categories based on LOS (Level of Service) changes (TRB, 2010). The total crashes in the before and after periods are 287 and 245, and the numbers of injury crashes in the before and after periods are 162 and 131, respectively.

Table 4-13: Descriptive Statistics of the Variables for Treated Sites

Variable Name	Definition	Mean	S.D.	Min.	Max.
Crash frequency in before period					
Total	Number of crashes for all crash types and all severity levels	8.2010	4.7938	2	24
Fatal+Injury	Number of crashes for all crash types and KABC severity levels	7.0069	3.7643	1	15
Crash frequency in after period					
Total	Number of crashes for all crash types and all severity levels	4.6297	2.6775	0	12
Fatal+Injury	Number of crashes for all crash types and KABC severity levels	3.7456	2.0609	0	8
Variables related to traffic and roadway geometric characteristics					
AADT_Before	Annual Average Daily Traffic (veh/day) in before period	41,073	8,361	20,500	60,683
AADT_After	Annual Average Daily Traffic (veh/day) in after period	40,960	8,020	25,500	57,979
LOS_Category	LOS E of 4-lane to LOS C of 6-lane = 53 sites, LOS E of 4-lane to LOS D of 6-lane = 37 sites, LOS D of 4-lane to LOS D of 6-lane = 48 sites				
Shld_Width_Before	Width of shoulder lane in before period (ft)	5.7714	2.5677	2	12
Shld_Width_After	Width of shoulder lane in after period (ft)	5.0857	1.9759	2	10
Narrowing_Shld_Width	1= Shoulder width was narrowed , 0=No changes	1 = 17.14%, 0 = 82.86%			
Med_Width_Before	Width of median in before period (ft)	29.8	11.844	6	48
Med_Width_After	Width of median in after period (ft)	23.371	8.5305	6	43
Narrowing_Med_Width	1= Median width was narrowed , 0=No changes	1 = 40.00%, 0 = 60.00%			
Max_Speed	Maximum Speed Limit (mph)	49.571	5.7358	40	60
Lane Width	Width of vehicle travel lane (ft)	11.805	0.472	10.667	13.333
Shld_Type	Type of shoulder (1 = paved, 0 = no)	1 = 77.14%, 0 = 22.86%			
Med_Type	Type of median (1 = with barrier, 0 = no barrier)	1 = 37.14%, 0 = 62.86%			

4.4.8 Increasing Lane Width; Shoulder Width; Median Width; Bike Lane Width on Urban Arterials

The RCI data and crash data for five years (2008-2012) were collected from the FDOT. The RCI data was obtained from the RCI historical database, and it provides current and historical roadway characteristics data and reflects the features of specific segments for selected dates. A segment is represented by roadway identification numbers and beginning and end mile points. A total of 6420 urban roadway segments with 2514.518 miles in length were identified for the analysis. Moreover, any missing values or errors of data were verified and corrected or removed using Transtat-Iview (a GIS searching system offered by FDOT) and Google Earth. The crash data were obtained from the CARS for target sites. Any crashes that occurred in the intersection influence area were removed for the analysis using the SITELOCA parameter (information for location of crash) in the CARS. Roadway characteristics data from RCI system for the target segments were matched with crash data by roadway ID and segment mile point for each segment. The descriptive statistics of the parameters for the target sites are presented in Table 4-14.

Table 4-14: Descriptive Statistics of the Variables

Variable	Mean	S.D.	Min.	Max.
Crash frequency				
Number of All (KABCO) crashes	16.522	25.431	0	356
Number of All (KABC) crashes	7.817	11.944	0	142
Number of All (KAB) crashes	3.723	5.868	0	58
Number of All (KA) crashes	1.157	2.355	0	52
Number of Bike (KABCO) crashes	0.384	0.964	0	16
Number of Bike (KABC) crashes	0.338	0.874	0	15
Number of Bike (KAB) crashes	0.228	0.646	0	12
Variables related to traffic and roadway geometric characteristics				
AADT (veh/day)	31880.44	16192.74	1,000	94,500
Length (mile)	0.392	0.417	0.101	4.985
Lane width (ft)	11.728	0.679	9	15
Posted speed limit (mph)	42.732	6.46	20	65
Visual interpretation of the pavement condition (0.00-5.00 scale)	3.752	2.378	1.50	5.00
Shoulder width (ft)	4.126	2.82	1	15
Bike lane width (ft)	3.632	2.571	2	7
Median width (ft)	22.499	12.286	2	100
Land Use	Central business district (CBD): 119 sites, Commercial: 3694 sites, Residential: 2607 sites			
Number of lanes	2-lane: 928 sites, 4-lane: 3188 sites, 6-lane: 2176 sites, 8-lane: 128 sites			

4.4.9 Lane Reduction; Adding a Bike Lane + Lane Reduction on Urban Arterials

For the analysis using the cross-sectional method, the road geometry data and crash records for roadway segments were collected for 3 years (2010-2012) from the RCI and CARS database as shown in Table 4-15. The AADT range of roadway segments is '2,000 ~ 50,000 veh/day' for urban four-lane arterials, respectively. The treatments are categorized as follow: 'conversion 4-

lane undivided to 3-lane roadways with TWLTL (Two-way Left-turn Lane)' as lane reduction and 'adding bike lanes + conversion 4-lane to 3-lane roadways with TWLTL' as lane reduction + adding a bike lane (i.e., Road diet).

Table 4-15: Summary of Data Description

Roadway Type	Treatment	Crash Records	Treated Sites		Reference Sites for SPFs	
Urban 4-lane undivided arterials	Lane reduction	2010~2012	219	77.032	344	104.864
	Road diet		31	11.97		

4.4.10 Resurfacing Urban Arterials

The road geometry data for urban arterials were collected for 4 years (2005-2008) before and 4 years (2010-2013) after periods. Also, crash records were collected for 4 years (2005-2008) before and 4 years (2010-2013) after periods from multiple sources maintained by the FDOT. These include the RCI and CARS database. A segment is represented by roadway identification numbers and beginning and end mile points. Roadway characteristics data from RCI system for the target segments were matched with crash data by roadway ID and segment mile point for each segment. A total of 195 and 205 urban segments with 115.443 and 122.515 miles in length were identified for the analysis as the treated and comparison sites, respectively. The descriptive statistics of the parameters for the treated sites are presented in Table 4-16.

Table 4-16: Descriptive Statistics of the Variables

Variable		Mean	S.D.	Min.	Max.
Number of crashes					
Before (2005-2008)	Number of KABCO crashes	5.933	7.823	0	45
	Number of KABC crashes	3.138	4.429	0	24
	Number of KAB crashes	1.923	2.986	0	14
After (2010-2013)	Number of KABCO crashes	5.938	8.033	0	44
	Number of KABC crashes	2.631	3.578	0	19
	Number of KAB crashes	1.626	2.402	0	13
Traffic and roadway geometric characteristics					
Before AADT (veh/day)		8658.621	7255.380	2100	40500
After AADT (veh/day)		8434.138	7097.997	2100	41000
Length (mile)		0.592	0.773	0.100	4.722
Average rate of heavy vehicle volume (% of AADT)		3.781	4.621	1.100	31.300
Number of lanes		2.072	0.532	1	4
Lane width (ft)		11.844	1.022	8.5	19
Shoulder width (ft)		5.367	2.893	1	12
Maximum speed limit (mph)		45.897	10.297	25	60

4.4.11 Adding Shoulder Rumble Strips on Freeways

The Installation of rumble strips on roadway shoulder is common treatment to improve safety. According to the HSM, the adding shoulder rumble strips on freeways treatment is safety effective in reducing run-off roadway crashes by 18% and 13% for all severities (KABCO) and injury crashes (KABC), respectively.

For the adding shoulder rumble strips on freeways treatment, the traffic and roadway geometric characteristics data for 3 years (2010-2012) was obtained from the RCI historical database, respectively. The data for freeways were collected where roadway geometric conditions of each segment have not been changed during the 3-year period. The roadway segments with shoulder rumble strips were determined based on the roadway ID, beginning mile post, end mile post, roadway functional class (FUNCLASS), and shoulder type (SHLDTYPE) in the RCI data.

Table 4-17 shows the number of roadway segments and total length of treated and reference sites. The range of AADT is specified in the description. Table 4-18 presents descriptive statistics of collected roadway and traffic parameters.

Table 4-17: Number of Roadway Segments and Length of Treated and Reference Sites

Treated Sites		Reference Sites	
Number of Segments	Total Length	Number of Segments	Total Length
1533	1267.231 mile	608	298.682 mile
AADT: 10,400~256,000			

Table 4-18: Descriptive Statistics of the Variables

Variable Name	Definition	Mean	S.D.	Min.	Max.
AADT	Annual Average Daily Traffic (veh/day)	79,122.73	52,229.02	10,400	256,000
Length	Roadway Segment Length (mile)	0.73	0.93	0.101	6.972
Shld_Width	Width of shoulder lane (ft)	9.92	1.74	0	22
Med_Width	Width of median (ft)	62.81	40.61	4	255
Max_Speed	Maximum Speed Limit (mph)	64.98	5.84	50	70
Lane_width	Width of vehicle travel lane (ft)	12.03	0.20	11	15.5
No_Lanes	Number of lanes in one direction	2.68	0.79	2	5

For the analysis of evaluation of CMF for the adding shoulder rumble strips on freeways treatment, crash records were collected for 5 years (2008-2012) from CARS database. The obtained crash records were matched with the target sites data based on roadway ID and milepost of each segment. Distributions of each crash type are summarized in Table 4-19.

Table 4-19: Descriptive Statistics of Crash Records

Crash type	Severity	Mean	S.D.	Min.	Max.
All crashes	KABCO	49.667	71.787	0	874
	KABC	22.596	31.476	0	366
	KAB	11.120	14.655	0	203
	KA	3.666	5.150	0	57
ROR crashes	KABCO	9.572	12.527	0	131
	KABC	5.082	6.525	0	69
	KAB	2.826	3.769	0	39
	KA	0.929	1.523	0	13

4.4.12 Adding Lanes by Narrowing Existing Lane Width on Freeways

According to the HSM, the adding lanes by narrowing existing lanes and shoulders on freeways treatment is increasing all types of crashes by 11% and 11% for all severities (KABCO) and injury crashes (KABC), respectively.

The traffic and roadway geometric characteristics data for 5 years (2008-2012) was obtained from the RCI historical database for the adding lanes by narrowing existing lanes and shoulders on freeways treatment, respectively. The data for freeways were collected where roadway geometric conditions of each segment have not been changed during the 5-year period. The 4-lane and 5-lane roadway segments in freeways were determined based on the roadway ID, beginning mile post, end mile post, roadway functional class (FUNCLASS), and number of lanes (NOLANES) in the RCI data.

Table 4-20 shows the number of roadway segments and total length of target sites. The range of AADT is specified in the description. Table 4-21 presents descriptive statistics of collected roadway and traffic parameters.

Table 4-20: Number of Roadway Segments and Length of Target Sites

Number of Lanes (one direction)	Total Length (mile)	Number of Segments
4	13.969	32
5	16.705	58
AADT (one direction): 70,000~150,000		

Table 4-21: Descriptive Statistics of the Variables

Variable Name	Definition	Mean	S.D.	Min.	Max.
AADT	Annual Average Daily Traffic (veh/day)	221,660.33	43,863.59	140,000	300,000
Length	Roadway Segment Length (mile)	0.34	0.28	0.101	1.548
Shld_Width	Width of shoulder lane (ft)	10.43	2.38	6	25
Med_Width	Width of median (ft)	37.24	35.64	12	240
Max_Speed	Maximum Speed Limit (mph)	59.28	6.16	45	65
Lane_width	Width of vehicle travel lane (ft)	12.36	0.48	12	13

Crash records were obtained for 5 years (2008-2012) from CARS database for the analysis of evaluation of safety effects for the adding lanes by narrowing existing lanes and shoulders on freeways treatment. The collected crash records were matched with the treated and untreated sites data based on roadway ID and milepost of each segment. Distributions of each crash type are summarized in Table 4-22.

Table 4-22: Descriptive Statistics of Crash Records

Crash type	Severity	Mean	S.D.	Min.	Max.
All crashes	KABCO	147.700	130.744	2	522
	KABC	66.678	59.564	2	244
	KAB	28.044	24.398	0	114
	KA	7.156	6.680	0	29

4.4.13 Installation of Roadside Barriers on Freeways

The road geometry data for roadway segments were obtained for 9 years (2003-2011) from the database of the RCI. In order to identify the treated sites on freeways, the financial management system was used. The financial management system offers a searching system named financial project search.

A total of 147 freeway segments totaling 68.168 miles were identified as treated sites with installation of roadside barriers during 2007. A segment is represented by roadway identification numbers, and beginning and end mile points. It was found that among the 147 treated sites, w-beam guardrails were implemented on 127 sites and concrete barriers were installed on 20 sites. In order to validate the treated locations from the financial management system, historical images from Google Street View were used. The barriers were installed on roadside when there were hazardous features such as trees, new poles, ditches, etc. Figure 4-5 presents an example of before and after location views for a specific treated location.

Before	After
	

Figure 4-5: Example of Before and After Treatment Conditions (Roadway ID: 10470000)

The crash records were obtained from CARS for the 4-year before (2003-2006) and 4-year after (2008-2011) periods. Also, the reference sites were identified using the RCI database. A total of 328 roadway segments with 119.899 miles in length were identified as reference sites. It is to be noted that reference sites are different than the comparison group; the reference sites are broader than the comparison group with more variation in AADT, roadway characteristics, and crash history to correct for the regression-to-the-mean threat. In order to account for these traffic parameter and multiple roadway characteristics, EB and FB techniques were applied in this study. The FB approach integrates the EB two-step into one and hence, FB utilizes information from a reference group of sites and the before information from the treated sites to estimate the long-term expected crash frequency. Table 4-23 presents a summary of distributions of each variable for the treated segments along with crash frequency.

Table 4-23: Descriptive Statistics of Treated Sites

(a) Roadway characteristics

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day) in before period	59,834.014	15,436.665	36,500	104,600
AADT (veh/day) in after period	56,636.735	14,903.484	35,000	104,200
Length (mile)	0.464	0.398	0.103	3.007
Numbers of lane	2.265	0.645	2	5
Surface width (ft)	27.184	7.734	24	60
Shoulder width (ft)	10.122	1.517	4	20
Median width (ft)	34.293	10.619	20	65
Curvature (Radius/5730ft)	0.468	0.802	0	3.05
Maximum speed limit (mph)	66.224	5.692	50	70
Distance to roadside barriers	13.272	3.493	9	30
Roadside barrier type	W-beam guardrails = 127sites, Concrete barrier = 20sites			

(b) Crash frequency

		Crash frequency in before period					Crash frequency in after period				
Crash Type	Severity	Mean	S.D.	Min.	Max.	Total	Mean	S.D.	Min.	Max.	Total
All crashes	KABCO	17.415	17.462	0	84	2,560	16.048	16.046	0	80	2,359
	KABC	8.497	8.803	0	48	1,249	7.204	7.544	0	43	1,059
	KAB	4.286	4.509	0	26	630	3.184	3.643	0	26	468
ROR crashes	KABCO	5.367	6.058	0	36	789	4.544	5.262	0	26	668
	KABC	2.925	3.302	0	17	430	2.231	2.669	0	14	328
	KAB	1.612	2.015	0	12	237	1.088	1.380	0	7	160

4.4.14 Widening Shoulder Width; Installation of Roadside Barriers + Widening Shoulder Width on Freeways

Both RCI and crash data were collected for five years (2008-2012) for the widening shoulder width and installation of roadside barrier + widening shoulder width treatments. The RCI data was obtained from the RCI historical database which provides current and historical roadway characteristics data and reflects the features of specific segments for selected dates. A total of 475 freeway segments with 188.067 miles in length were identified for the analysis. Moreover, any missing values or errors of data were verified and corrected or removed using Transtat-Iview and Google Earth. The descriptive statistics of the parameters for the treated sites are presented in Table 4-24.

Table 4-24: Descriptive Statistics of Target Segments

(a) Roadway characteristics

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day)	60437.474	22062.895	27000	108300
Length (mile)	0.396	0.380	0.1	3.22
Numbers of lane	2.684	0.799	2	6
Surface width (ft)	32.198	9.6	23	72
Shoulder width (ft)	9.935	1.613	4	20
Median width (ft)	45.56	25.742	6	90
Curvature (Radius/5730ft)	0.377	0.678	0	7
Maximum speed limit (mph)	66.074	3.992	50	70
Roadside Barrier	Segments with roadside barrier: 147 sections, No roadside barrier: 328 sections			

(b) Crash frequency

		Crash frequency in before period			
Crash Type	Severity	Mean	S.D.	Min.	Max.
All crashes	KAB	2.606	3.350	0	27
ROR crashes	KABC	2.002	2.789	0	24
	KAB	0.804	1.161	0	10

4.4.15 Converting a Minor-road Stop-controlled Intersection to a Modern Roundabout

It is widely used roadway geometry design in Florida and many other states to install modern roundabout to increase efficiency and safety comparing to stop controlled and signalized controlled intersections. Figure 4-6 presents the geometry design of modern roundabout. The entering traffic has to give way or yield the circulating traffic. This design may potentially help traffic from locking up and reduce angle crashes.

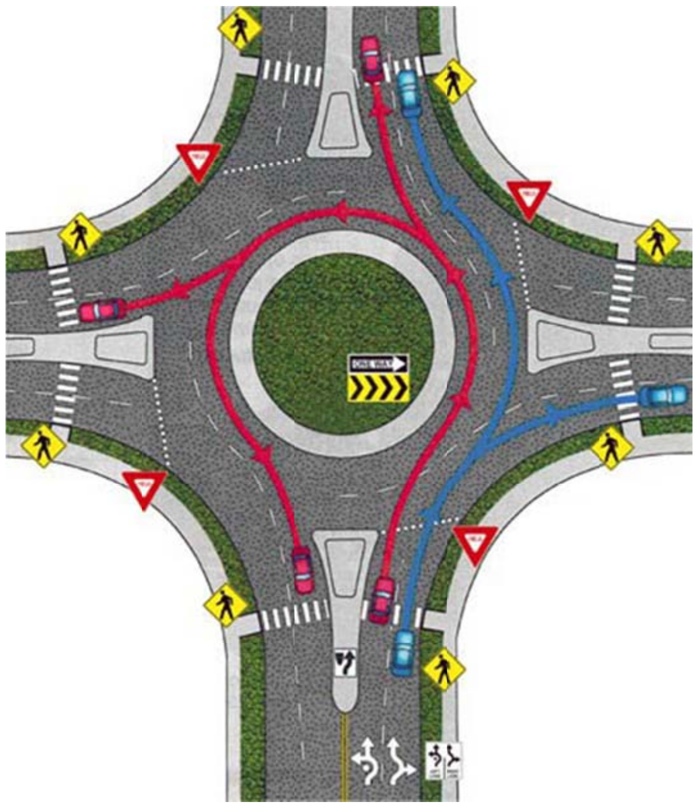


Figure 4-6: Design of Modern Roundabout

For the Converting a minor-road stop-controlled intersection to a modern roundabout treatment, the intersection data is collected from RCI historical database. According to RCI Field Handbook, we collect variable “ROTARY” to identify the location of modern roundabout. In the statement, the value “1” represents roundabout, “2” represents traffic circle, and “3” represents mini-roundabout. As we check each code detail, we identify “1” is the modern roundabout. We found that roundabout is a popular traffic control design in the State of Florida. Based on our query from RCI, a total 190 modern roundabouts has been identified. As we observed, many of the modern roundabouts are concentrated in urban areas, especially on the east coast. Figure 4-7 presents locations of roundabout and all way stop intersections.

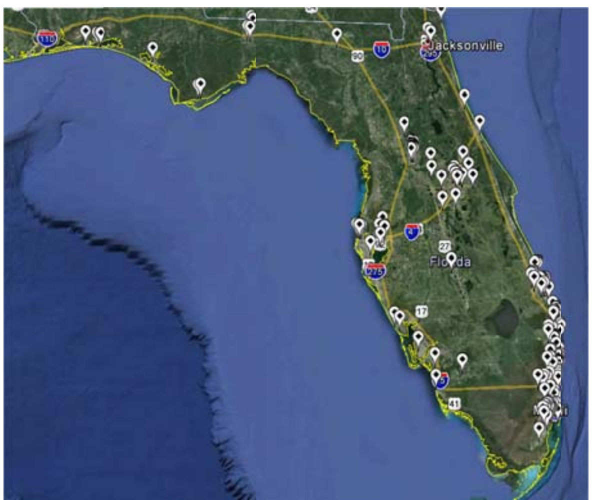
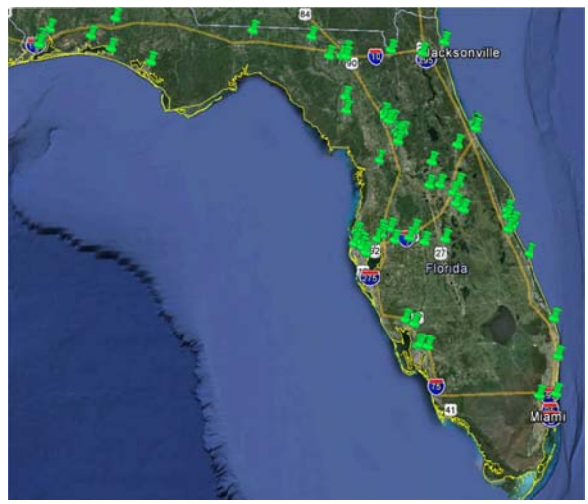
Roundabouts (190 sites)	All way stop controlled intersections (99 sites)
	

Figure 4-7: Locations of Roundabouts and Intersections

The descriptive statistics can be presented in the exploratory analysis as shown below. Since these locations are located at mostly rural area, the exposure of crash is lower due to the low volume. Thus, longer crash record was used for 11 years from 2003 to 2013 from CARS database and Signal for Analytics. The obtained crash records were matched with the target sites data based on its lat-long for each intersection influence area. Descriptive statistics for each crash type are summarized in Table 4-25.

Table 4-25: Descriptive Statistics of Crash Records for Roundabout (N=99)

Crash types (Severity)	Mean	S.D.	Min.	Max.
All (KABCO)	3.616	3.683	0	15
All (KABC)	1.505	1.809	0	8

We also check the descriptive statistics for comparison sites. The comparison sites are four-legged stopped-controlled intersections. It is proper to compare four-way stopped controlled intersections with roundabout. Because these two intersection control types usually have low traffic volume and also similar roadway features. Based on Table 4-26, we can tell the All (KABCO) crashes are higher than what's shown in Table 4-25 by 14 percent. However, the All (KABC) crashes are opposite, which 4-legged stop-controlled intersections are lower in fatal and injury crashes.

Table 4-26: Descriptive Statistics of Crash Records for 4ST Intersections (N=102)

Crash types (Severity)	Mean	S.D.	Min.	Max.
All (KABCO)	4.127	5.507	0	43
All (KABC)	1.471	1.756	0	10

4.4.16 Adding Right Turn Lane at Signalized Intersections

It is a very common type of geometry design to install an exclusive right turn lane at intersections. According to previous research, exclusive right turn lane improves the efficiency of traffic flow by providing right turn pocket. This way the right turn traffic would not block the through traffic and thus improve the service level. On the other hand, the safety effect of right turn lane is not certain. Therefore this part will focus on identifying whether right turn lane has impact on signalized intersection or not. Figure 4-8 shows the sample images of right turn lane and isolated right turn lane.

Right turn lane	Isolated right turn lane
	

Figure 4-8: Right Turn Lane and Isolated Right Turn Lane at Intersections

To verify the safety effect of the exclusive right turn lane, 171 rural signalized intersections have been located. The reason why we choose rural road is due to that the majority intersection at urban area has exclusive right turn lane, and this may lead to imbalance samples. Therefore, we query the intersection through the variables provided in RCI for the adding right turn channelization treatment. By selecting the signalized intersections in rural area, we look into the existence of exclusive right turn lane for each location with major and minor traffic volume available. Table 4-27 presents sample size of treated and comparison sites for each type of right turn lanes.

Table 4-27: Sample Size for Each Type of Right Turn Lane

Roadway Types	Treated Group	Comparison Group
Major RTL	100	71
Minor RTL	78	93
Isolate Major RTL	34	137
Isolate Minor RTL	36	135

Note: RTL=Right turn lane

The descriptive statistics can be presented in the exploratory analysis as shown below. We set our target in rural area. The crash records are collected from 2003 to 2013 from CARS database. The obtained crash records were matched with the target sites data based on its lat-long for each intersection influence area. Descriptive statistics for intersections with exclusive right turn lane are summarized in Table 4-28.

Table 4-28: Descriptive Statistics of Crash Records for Intersection with RTL

All (KABCO) Crashes	No. of Observation	Mean	Standard Deviation	Minimum	Maximum
Major RTL	71	32.887	32.770	0	160
Minor RTL	93	36.699	33.727	0	188
Isolate Major RTL	137	41.927	43.371	0	294
Isolate Minor RTL	135	42.156	39.496	0	294

We also check the descriptive statistics for comparison sites. The comparison sites are intersections without right turn lanes. Descriptive statistics for intersections without exclusive right turn lane are summarized in Table 4-29. Based on Table 4-29, the intersections without RTL has more crashes comparing to those with RTL.

Table 4-29: Descriptive Statistics of Crash Records for Intersections without RTL

All (KABCO) Crashes	No. of Observation	Mean	Standard Deviation	Minimum	Maximum
Major RTL	100	56.70	49.054	3	294
Minor RTL	78	58.91	52.399	4	294
Isolate Major RTL	34	66.59	44.247	4	188
Isolate Minor RTL	36	64.36	57.058	9	264

4.4.17 Adding Left Turn Lane at Signalized Intersections

The adding left turn channelization treatment is common roadway design at intersections. Based on previous researches, exclusive left turn lane improves the efficiency of traffic flow by providing left turn pocket. In detail, left turn traffic would not block the through traffic and thus improve the level of service. However, the safety effect of left turn lane is not certain. Therefore, this part will focus on identifying whether left turn lane has impact on signalized intersection or not. Figure 4-9 shows the sample images of left turn lane and isolated left turn lane.

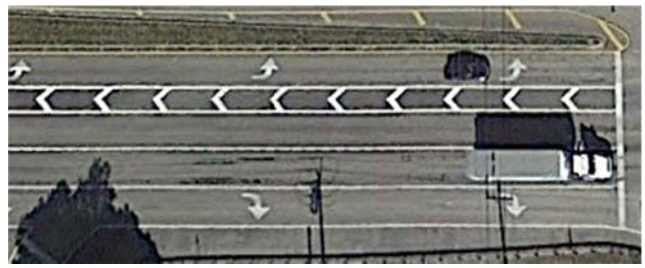
Left turn lane	Isolated left turn lane
	

Figure 4-9: Right Turn Lane and Isolated Right Turn Lane at Intersections

In order to estimate the safety effect of the exclusive left turn lane, 171 rural signalized intersections have been located. We query these intersections through the variables provided in RCI. By selecting the signalized intersections in rural area, we look into the existence of exclusive left turn lane for each location with major and minor traffic volume available. Table 4-30 presents sample size of treated and comparison sites for each type of left turn lanes.

Table 4-30: Sample Size for Each Type of Left Turn Lane

Roadway Types	Treated Group	Comparison Group
Major LTL	152	19
Minor LTL	99	72
Isolate Major LTL	13	158
Isolate Minor LTL	5	166

Note: LTL=Left turn lane

The descriptive statistics can be presented in the exploratory analysis as shown below. We set our target in rural area. The crashes are collected from 2003 to 2013 from CARS database. The obtained crash records were matched with the target sites data based on its lat-long for each intersection influence area. Descriptive statistics for intersections with exclusive left turn lane are summarized in Table 4-31.

Table 4-31: Descriptive Statistics of Crash Records for Intersection with LTL

All (KABCO) Crashes	No. of Observation	Mean	Standard Deviation	Minimum	Maximum
Major LTL	152	49.342	50.9	0	294
Minor LTL	99	52.788	51.058	0	294
Isolate Major LTL	13	87.385	76.524	9	294
Isolate Minor LTL	5	113.6	116.528	12	294

We also check the descriptive statistics for comparison sites. The comparison sites are intersections without left turn lanes. Descriptive statistics for intersections without exclusive left turn lane are summarized in Table 4-32. Based on Table 4-32, we can tell that the intersections with LTL have more crashes than those without.

Table 4-32: Descriptive Statistics of Crash Records for Intersection without LTL

All (KABCO) Crashes	No. of Observation	Mean	Standard Deviation	Minimum	Maximum
Major LTL	19	26.737	26.411	3	105
Minor LTL	72	38.639	32.103	3	188
Isolate Major LTL	158	43.494	39.389	0	264
Isolate Minor LTL	166	44.819	39.674	0	264

4.4.18 Changes of Median Width on Signalized Intersections

Many researches set the focus on identifying the safety effect of changing median width for roadway segments. However, the safety effect for the Increasing intersection median width at signalized intersections treatment is uncertain. Therefore, our goal is to identify whether the median width is a crucial factor for intersection as well.

We first collect a pool of intersection with different median width based on the information in RCI. Then the median width for each location is measured in google earth. A total of 171 signalized intersections are targeted. By comparing the different median width and other important variables, we would able to analyze whether median width is an important contributing factor to the safety of intersections. Table 4-33 presents descriptive statistics of target sites.

Table 4-33: Descriptive Statistics of Target Intersections

	Mean	Standard Deviation	Minimum	Maximum
Median Width Major (ft)	10.12	12.831	0	52.42
Median Width Minor (ft)	2.291	9.314	0	99.25

We set our target in rural area. The crash records are collected from 2003 to 2013 from CARS database. The obtained crash records were matched with the target sites data based on its lat-long for each intersection influence area. Descriptive statistics for intersections with different median width at the major roads and the minor road are summarized in Table 4-34. In preliminary analysis, we set a threshold to separate all intersections into two groups. This threshold was selected based on 50 percentile from the data which is also called the median. After the median is calculated, the descriptive statistics is listed. As shown in Table 4-34, wider median width results in more crashes. Besides, this applies to the major road and the minor road.

Table 4-34: Descriptive Statistics of Target Intersections

Crash types (Severity)	No. of Observation	Mean	Standard Deviation	Minimum	Maximum
Major Road Median <= 5.49 feet					
All (KABCO)	86	39.174	47.799	0	294
All (KABC)	86	20.035	23.830	0	147
Major Road Median > 5.49 feet					
All (KABCO)	85	54.576	39.739	2	188
All (KABC)	85	30.553	21.942	1	91
Minor Road Median = 0 feet					
All (KABCO)	150	41.907	36.569	0	264
All (KABC)	150	23.153	20.983	0	147
Major Road Median > 0 feet					
All (KABCO)	21	82.000	73.528	12	294
All (KABC)	21	40.333	33.464	9	127

4.4.19 Changes of Intersection Angle Level

We collected the intersections with diverse skew-angle. The skew angle were measured for each intersection located in google earth. A total of 171 signalized intersection are targeted. The descriptive statistics for skew angle is shown in Table 4-35. By comparing the different skew angle and other important variables, we are able to analyze whether skew angle is an important contributing factor to the safety of intersections.

Table 4-35: Descriptive Statistics of Target Intersections

Roadway Types	Average	Standard Deviation	Min	Max
Skew Angle	15.56	22.15	0.00	80.00

4.4.20 Installation of Retroreflective Border Back Plates

Retroreflective backplates (Figure 4-10) intersection sites were retrieved from the City of Orlando. In addition, all members of the research team also reported the location from their personal commutes. Intersection sites were then verified using Google Maps. Google Maps was then used to record the latitude and longitude of the intersection. Using Google Maps time lapse we were then able to identify a date at which the retroreflective backplates was present and a date at which it was not present. These two dates were then used to identify a window of time where the retroreflective backplates of the signal was installed. This information gives a comparable time period for the intersection for before and after the installation.

Figure 4-10: Example of Retroreflective Border Backplate at Signalized Intersection

After collecting longitudes and latitudes of the retroreflective backplates signal intersections, Transtat I-View maintained by FDOT is used to collect the major and minor roadway ID's and center points. Google Earth was also used to collect the AADT for the major and minor roadways, as well as the intersection length on the major and minor roads. It was then recorded based on Google Earths current data if a retroreflective backplate is present or not for the major and minor roadways. Using Google Maps, it was recorded for the intersections that were updates if there was a change in number of signals for both the major and minor roadways upon the change to a signal with retroreflective backplates.

We have located 51 intersections with retroreflective backplates, however, most of these intersection were installed recently after 2014. Therefore, we are not able to perform before-after study based on all of these 51 intersections. Instead, 3 intersections were found to have retroreflective backplates installed in 2008 which we are able to retrieve crash count for 4 years before and 4 years after. The period for before data is 2004-2007 and that for after data is 2009-2012. After collecting 51 sites, we went back to each individual location and found intersections that do not have retroreflective backplates on their signals to use as a control. This was done by going to each location on Google Maps and identifying nearby intersection along the same major roadway that had a similar design scheme and did not have a retroreflective backplates. The name of the intersection and its latitude and longitude were then recorded along with the number that corresponds to the intersection that it is being compared to.

4.4.21 Installation of Red Light Running Warning Sign with Citation Amount Specified at Upstream of the Intersection

The locations of the warning signs for red light running violation were retrieved from the Department of Traffic Engineering in Orange County. However, we did not have the installation date for these locations, thus we cannot perform before and after study. In this case, we matched crashes from 2010 to 2012 to perform cross-sectional study. We have 53 intersections with the warning signs. To ensure the data quality, we checked the history images at these locations in Google Map to confirm that these signs were not added during these period. For the reference sites, we located 37 reference intersections without warning signs. These locations are close to the sites with the warning signs. In addition, for all sites were confirmed that there was no major change in these 3 years. Figure 4-11 presents an example of warning sign with citation amount for red-light running violation.

Figure 4-11: Example of Red Light Running Warning Sign with Citation Amount

4.4.22 Converting Traditional and Hybrid Toll Plazas to All Electronic Toll Collection

Expressways (toll roads) play a pivotal role in meeting the world's transportation needs. According to the FDOT (2014), toll road miles have almost doubled in Florida in the past decade. This interest has created a need for understanding the safety effect of the toll collection systems. However, the safety effect for the converting traditional and hybrid mainline toll plazas to all electronic toll collection treatment is uncertain. Figure 4-12 presents images of Traditional Mainline Toll Plaza (TMTP), Hybrid Mainline Toll Plaza (HMTP), and All-electronic toll collection (AETC).

Traditional Mainline Toll Plaza (TMTP)

Hybrid Mainline Toll Plaza (HMTP)

All-electronic toll collection (AETC)

Figure 4-12: Images of Traditional Mainline Toll Plaza (TMTP), Hybrid Mainline Toll Plaza (HMTP), and All-electronic Toll Collection (AETC)

AETC is expanding on the Florida Turnpike (FT). Since spring 2011 FT started removing the TMTP and HMTP and adopting the AETC system and the toll-by-plate (TBP) program. After successfully adopting this system in Miami-Dade County's toll plazas in spring 2011, it was scheduled to be done in other FT facilities. For example, Fort Lauderdale and Tampa Bay scheduled for spring 2014 and summer 2014, respectively. The treated sites and reference locations were identified from the publication reports of Central Florida Expressway Authority (CFX, 2014). Table 4-36 presents descriptive statistics of target sites.

Table 4-36: Descriptive Statistics of Target Locations

	Number of Sites	Average AADT in Before Period (veh/day)	Average AADT in After Period (veh/day)
Reference sites (TMTP)	42	28,007	32,234
TMTP to HMTP	30	30,914	33,908
TMTP to AETC and, HMTP to AETC	16	79,733	93,576

For the converting traditional and hybrid mainline toll plazas to all electronic toll collection treatment, crash records for 7 years were collected for 7 years (2008-2014). Table 4-37 presents descriptive statistics of crash records for treated and reference sites. It was found from the comparison of crash records that after converting traditional and hybrid mainline toll plazas to all electronic toll collection treatment, average number of crashes was reduced by 26% for the treated sites whereas it was reduced by 6% for the reference sites. This indicates that the treatment is effective in reducing crashes.

Table 4-37: Descriptive Statistics of Crash Records

	Number of Sites	Average Number of All (KABCO) Crashes	
		Before Period	After Period
Reference sites (TMTP)	42	32.2	30.1
TMTP to AETC and, HMTP to AETC	16	17.8	13.1

4.4.23 Converting HOV Lanes to HOT Lanes

For the evaluation of safety effects for the converting high-occupancy vehicle (HOV) lanes to high-occupancy toll (HOT) lanes treatment, data from 16 miles of 95-Express (two directions) on I-95 in the southeast of Florida was used. This section was divided to 20 segments based on the number of lanes and the values of the AADT. To select reference segments with similar characteristic to the 95-Express section, a 156 reference segments located on approximately 256 miles on I-95 were used to evaluate this application. Crash data for a nine-year period (2005-2013) was investigated to examine the safety impact by evaluating crashes for a period of three years before and three years after the upgrading. Crashes that occurred within these segments were extracted from the crash database maintained by FDOT known as a CARS. It should be noted that data in the period when 95-Express were being implemented (2008–2010) was excluded from the analysis.

CHAPTER 5. ROADWAY SEGMENTS

5.1 Adding Shoulder Rumble Strips; Widening Shoulder Width; Adding Shoulder Rumble Strips + Widening Shoulder Width on Rural Two-lane Roadways

5.1.1 Safety Performance Functions

Four full SPFs were developed using the NB model for the four combinations of crash type and severity levels: 1) All crashes (KABCO), 2) All crashes (KABC), 3) SVROR (KABCO), and 4) SVROR (KABC) using the 2-year before and 2-year after crash data as shown in Table 5-1. To reflect the nonlinear relationship between AADT and crash frequency, logarithm of AADT was used instead of AADT). In general, the results of the four full SPFs show that crash frequency is higher for the roadway segments with higher AADT and longer length. It is worth noting that the crash frequency in the after period is lower than the before period for both All and SVROR crashes and this trend is consistent with the declining trend of traffic crashes over the last eight years (2004~2011) in the United States (NHTSA, 2013). Since this declining trend of traffic crashes is not only based on AADT, one explanatory variable (i.e., Time Difference) is included in the model to account for the time difference between before and after periods. For example, the difference between predicted crash counts for before and after periods are mostly based on AADT changes even when simple or full SPF is applied since we assume that there are no geometric changes (i.e., treatment) during before and after periods except AADT.

Table 5-1: Florida Specific Calibrated SPFs for Rural Two-lane Roadways by Crash Type and Severity Level

Coefficient						AIC
	Intercept	Log (ADT)	Time Difference (Before Period)	Surface Width (Total Lane Width)	Dispersion coefficient	
Crash Type (Severity)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	
All (KABCO)	-16.0913 (<0.0001)	0.9309 (<0.0001)	0.1078 (0.0571)	0.3702 (<0.0001)	-0.7693 (<0.0001)	13,944
All (KABC)	-16.6181 (<0.0001)	0.8693 (<0.0001)	0.1269 (0.0274)	0.3896 (<0.0001)	-0.5623 (<0.0001)	10,722
SVROR (KABCO)	-14.2772 (<0.0001)	0.3758 (<0.0001)	0.1324 (0.0884)	0.4182 (<0.0001)	-0.7034 (<0.0001)	5,139.9
SVROR (KABC)	-13.6972 (<0.0001)	0.2740 (<0.0001)	0.1832 (0.0549)	0.4114 (<0.0001)	-1.1174 (<0.0001)	3,831.4

5.1.2 Crash Modification Factors

The CMFs estimated using the observational before-after with EB method are presented in Table 5-2. Generally, the safety effects of SRS, WSW, and SRS+WSW were positive for both All and SVROR crashes. Moreover, the CMFs for SVROR (KABCO) crashes are lower than the CMFs for All (KABCO) crashes. These results indicate that the SRS, WSW, and SRS+WSW are more effective in reducing SVROR crashes. It is worth to note that due to the low frequency of SVROR (KABC), the estimated CMFs are not significant at the 90% confidence level. Although the CMFs that are not significant at 90% confidence level may not represent reliable safety effects of treatments statistically, it can be suggested to use the insignificant CMFs to check the general impact of treatments with relatively large variation.

Table 5-2: Evaluated CMFs by EB Method

	Shoulder Rumble Strips (SRS)		Widening Shoulder Width (WSW)		Shoulder Rumble Strips + Widening Shoulder Width (SRS+WSW)	
Crash Type (Severity)	CMF	S.E	CMF	S.E	CMF	S.E
All (KABCO)	0.83**	0.07	0.87**	0.05	0.75**	0.10
All (KABC)	0.84*	0.08	0.89**	0.06	0.78*	0.11
SVROR (KABCO)	0.75*	0.14	0.82*	0.10	0.68*	0.17
SVROR (KABC)	0.80	0.16	0.87	0.12	0.75	0.21

**: significant at a 95% confidence level, *: significant at a 90% confidence level

5.1.3 Crash Modification Functions

Generally, the variation of CMFs with different roadway characteristics among treated sites is ignored because the CMF is a fixed value that represents overall safety effects of the treatment for all treated sites. Thus, the CMFunctions have been utilized to determine the relationship between the safety effects and roadway characteristics. The CMFunctions of SRS, WSW and SRS+WSW were also developed in order to observe the general relationships between CMFs and the original shoulder width of roadway segments in the before period. The CMFs were estimated for the treated sites with different shoulder widths and used to develop CMFunctions. The range of standard errors of CMFs for different shoulder width was 0.05 to 0.3, but the standard errors were less than 0.2 for most of CMFs. The HSM suggests that a standard error of 0.1 or less indicates that the CMF value is sufficiently accurate, precise, and stable. Also, for treatments that have CMFs with a standard error of 0.1 or less, other related CMFs with standard errors of 0.2 to 0.3 may also be included to account for the effects of the same treatment on other facilities, other crash types or other severities. Due to low frequency of SVROR (KABC) crashes, the CMFuntions were developed for All crashes and SVROR (KABCO). Twelve linear and nonlinear regression functions (Table 5-3) were compared and the best fitted function was identified based on the adjusted R-squared value. To ensure that the CMF value from CMFunction cannot be negative estimate, log form of linear and nonlinear models were utilized (Sacchi and Sayed, 2014). It was found that linear and two nonlinear functional forms (power, power 2) are the best fitted functions for this relationship.

Table 5-3: Log Linear and Nonlinear Functional Forms

Function Name	Equation
Linear	$Ln(Y) = A + (B_1 \cdot X)$
Inverse	$Ln(Y) = A + (B_1 / X)$
Exponential	$Ln(Y) = A + exp(B_1 \cdot X)$
Log	$Ln(Y) = A + (B_1 \cdot log\ X)$
Power	$Ln(Y) = A + (X^{B_1})$
Power 2	$Ln(Y) = A + (X^{B_1}) + (X^{B_2})$
Quadratic	$Ln(Y) = A + (B_1 \cdot X) + (B_2 \cdot X^2)$
Polynomial	$Ln(Y) = \{(B_1 \cdot X) + (B_2 \cdot X^2) + (B_3 \cdot X^3)\} \times \exp(B_4 \cdot X)$
Polynomial 2	$Ln(Y) = \{A + (B_1 \cdot X) + (B_2 \cdot X^2)\} \times \exp(B_4 \cdot X)$
Power_Exponential	$Ln(Y) = \{(B_1 \cdot X) + (X^{B_2})\} \times \exp(B_4 \cdot X)$
Power_Exponential 2	$Ln(Y) = \{A + (X^{B_1})\} \times \exp(B_2 \cdot X)$
Power_Exponential 3	$Ln(Y) = \{A + (X^{B_1}) + (X^{B_2})\} \times \exp(B_3 \cdot X)$

Tables 5-4, 5-5, and 5-6 present the developed CMFunctions of SRS, WSW and SRS+WSW for All (KABCO), All (KABC) and SVROR (KABCO), respectively. The CMFunction is defined as the function of original shoulder width of roadway segments for the CMF. In other words, Y and X represent the CMF and original shoulder width in each CMFunction. The relationship between

CMFs and the original shoulder width indicates that the safety effects of two single treatments and combination are higher for the segments with narrower shoulder width. In other words, crash frequencies are more likely to decrease if the treatment is applied to the segments with narrower shoulder width. Moreover, for both All (KABCO) and All (KABC) crashes, SRS is more safety effective for roadway segments with shoulder width of 10ft or above and 9.5ft or above, whereas WSW is more safety effective for roadway segments with shoulder width less than 10ft and 9.5ft. It was also found that for SVROR (KABCO) crashes, SRS is more safety effective for roadway segments with shoulder width of 7.5ft or above, whereas WSW is more safety effective for roadway segments with shoulder width less than 7.5ft. It is worth to note that the difference between CMFs of two single treatment and CMFs for multiple treatments is getting larger as shoulder width decreases for both All and SVROR crashes. The results indicate that the safety effects of multiple treatments vary based on characteristics of roadway segments.

Table 5-4: Developed CMFunctions for All Crashes (KABCO)

(a) Shoulder Rumble Strips (SRS)

Functional Form = Power				
Parameter	Coefficient	Standard error	t-value	p-value
A	-1.3469	0.0186	-72.29	<0.0001
B_1	0.0782	0.0084	9.36	0.0007
Root Mean Squared Error (Root_MSE) = 0.0158 R-Square = 0.9450 Adj. R-Square = 0.9313				

(b) Widening Shoulder Width (WSW)

Functional Form = Linear				
Parameter	Coefficient	Standard error	t-value	p-value
A	-0.4223	0.0272	-15.55	<0.0001
B_1	0.0275	0.0035	7.90	0.0014
Root Mean Squared Error (Root_MSE) = 0.0292 R-Square = 0.9398 Adj. R-Square = 0.9247				

(c) Shoulder Rumble Strips + Widening Shoulder Width (SRS+WSW)

Functional Form = Power				
Parameter	Coefficient	Standard error	t-value	p-value
A	-1.7575	0.0397	-44.23	<0.0001
B_1	0.1902	0.0140	13.60	0.0002
Root Mean Squared Error (Root_MSE) = 0.0370 R-Square = 0.9639 Adj. R-Square = 0.9549				

Table 5-5: Developed CMFunctions for All Crashes (KABC)

(a) Shoulder Rumble Strips (SRS)

Functional Form = Power 2				
Parameter	Coefficient	Standard error	t-value	p-value
A	-2.2562	0.0169	-133.75	<0.0001
B_1	0.1780	0.0097	18.35	0.0004
B_2	-0.2080	0.0337	-6.16	0.0086
Root Mean Squared Error (Root_MSE) = 0.0054 R-Square = 0.9951 Adj. R-Square = 0.9918				

(b) Widening Shoulder Width (WSW)

Functional Form = Linear				
Parameter	Coefficient	Standard error	t-value	p-value
A	-0.4917	0.0375	-13.11	0.0002
B_1	0.0370	0.0048	7.68	0.0015
Root Mean Squared Error (Root_MSE) = 0.0403 R-Square = 0.9365 Adj. R-Square = 0.9206				

(c) Shoulder Rumble Strips + Widening Shoulder Width (SRS+WSW)

Functional Form = Power				
Parameter	Coefficient	Standard error	t-value	p-value
A	-1.8010	0.0475	-37.94	<0.0001
B_1	0.2093	0.0160	13.05	0.0002
Root Mean Squared Error (Root_MSE) = 0.0449 R-Square = 0.9589 Adj. R-Square = 0.9487				

Table 5-6: Developed CMFunctions for SVROR Crashes (KABCO)

(a) Shoulder Rumble Strips (SRS)

Functional Form = Power				
Parameter	Coefficient	Standard error	t-value	p-value
A	-1.5106	0.0182	-83.06	<0.0001
B_1	0.1110	0.0076	14.61	0.0001
Root Mean Squared Error (Root_MSE) = 0.0159 R-Square = 0.9746 Adj. R-Square = 0.9682				

(b) Widening Shoulder Width (WSW)

Functional Form = Linear				
Parameter	Coefficient	Standard error	t-value	p-value
A	-0.5390	0.0344	-15.67	<0.0001
B_1	0.0362	0.0044	8.20	0.0012
Root Mean Squared Error (Root_MSE) = 0.0369 R-Square = 0.9439 Adj. R-Square = 0.9298				

(c) Shoulder Rumble Strips + Widening Shoulder Width (SRS+WSW)

Functional Form = Power				
Parameter	Coefficient	Standard error	t-value	p-value
A	-2.0666	0.0505	-40.96	<0.0001
B_1	0.2467	0.0157	15.70	<0.0001
Root Mean Squared Error (Root_MSE) = 0.0490 R-Square = 0.9684 Adj. R-Square = 0.9605				

5.2 Increasing Lane and Shoulder Widths at Straight and Curved Rural Two-lane Roadways

5.2.1 Nonlinearizing Link Function

To account for the nonlinear effect of lane width on crashes, the nonlinearizing link function was developed based on the relationship between the logarithm of crash rates (ln(CR)) and lane width as presented in Figure 5-1. Crash rate was defined as the number of crashes per mile. It is worth noting that the interaction effects between the crash rates and other explanatory variables were also investigated, but it did not capture the nonlinear effects from any other parameters. A linear regression line was also fitted to the observed data but it does not reflect the nonlinearity of each predictor. It was found that the observed crash rate initially decreased as lane width increases to 11.5 ft but it increased when the lane width was greater than 11.5 ft. The crash rates start to decrease again after 12.5 ft. The nonlinearizing link function was derived based on those three ranges of lane width as shown in following Equation (5-1). The developed nonlinearizing link function can be used as a nonlinear predictor in the analysis to improve model fit (Lao et al., 2013; Park and Abdel-Aty, 2015a).

$$U_{LW}\begin{cases} = 0.99 - 0.09(LaneWidth - 11.5) & LaneWidth \leq 11.5 \\ = 1.00 - 0.08(LaneWidth - 12.5)^2 & 11.5 < LaneWidth \leq 12.5 \\ = 0.14 - 0.38(LaneWidth - 15.0) & 12.5 < LaneWidth \end{cases} \quad (5\text{-}1)$$

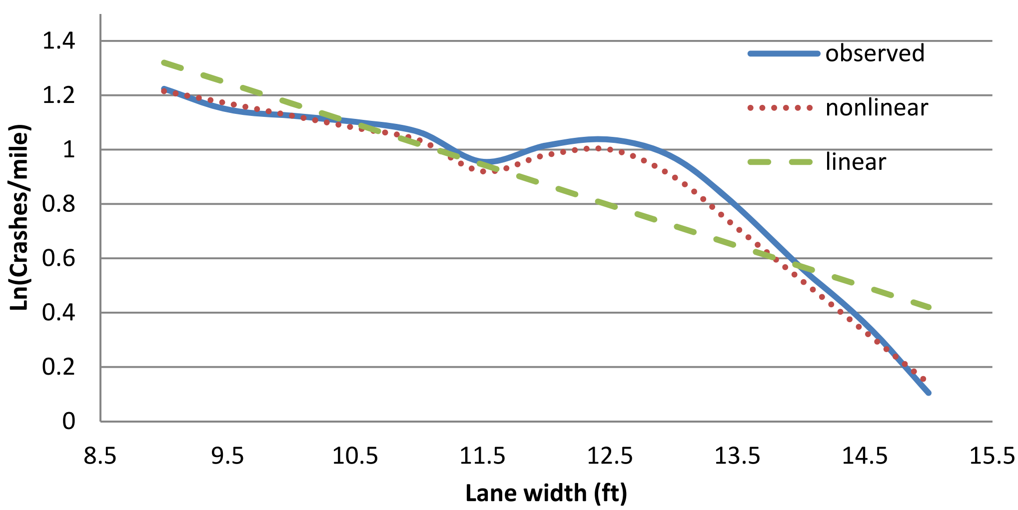


Figure 5-1: Development of Nonlinearizing Link Function

5.2.2 Generalized Nonlinear Models

Table 5-7 presents the developed GNMs and generalized linear models (GLMs) for different crash severities. The GNMs were developed using the nonlinearizing link function (U_{LW}) and the GLMs were also estimated to compare model performance. According to Aarts and Van Schagen (2006), Lee et al., (2015), and Park and Abdel-Aty (2015a), it is worth to investigate interaction impacts among multiple roadway characteristics, and inclusion of interaction terms can improve the model fit. It was found that the GNMs with multiple interaction terms (Ln(AADT) × U_{LW}, Ln(AADT) × Shoulder width, Curve × Shoulder width × Lane width, Curve × Ln(Segment length)) provided better model performance (i.e., smaller AIC value) than the GLMs. In detail, the results show that both lane and shoulder widths interacts with AADT. The results also show that there is an interaction impact between lane and shoulder widths at curved section. It should be noted that an interaction term between lane and shoulder widths at non-curved section was also utilized but it was not significant for all types of different severity levels. This may be because both increasing lane width and a wider shoulder at curved segments are effective in reducing specific crash types (e.g., run-off roadway, single vehicle crashes, etc.) whereas both treatments at non-curved segments are helpful for reducing multiple crash types and each treatment can be more effective to decrease specific crash type in different conditions at the same time. Lastly, the logarithm of segment length at curved segments was found to be significant.

Table 5-7: Estimated Parameters of GLMs and GNMs with Interaction Terms

(a) GNM with U_{LW}

	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-6.3034	0.4717	<0.0001	-7.1376	0.4748	<0.0001	-7.2995	0.4918	<0.0001
Ln(AADT)	0.7517	0.0949	<0.0001	0.7957	0.0989	<0.0001	0.7746	0.1028	<0.0001
Segment length	0.5119	0.0255	<0.0001	0.5323	0.0251	<0.0001	0.5335	0.0253	<0.0001
Ln(AADT)×U_{LW}	0.1526	0.0749	0.0416	0.1414	0.0795	0.0753	0.1380	0.0826	0.0948
Ln(AADT)×Shoulder width	-0.0191	0.0015	<0.0001	-0.0201	0.0016	<0.0001	-0.0206	0.0016	<0.0001
Curve ×Shoulder width×Lane width	0.0066	0.0023	0.0045	0.0071	0.0023	0.0018	0.0062	0.0024	0.0084
Curve × Ln(Segment length)	0.4402	0.1656	0.0078	0.5125	0.1726	0.0030	0.6500	0.1935	0.0008
Dispersion	2.8910			2.5436			2.4095		
Log likelihood	-5548.6478			-4465.8456			-3785.0021		
AIC	11113.2955			8947.6911			7586.0042		

(b) GLM

	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-4.5041	0.7905	<0.0001	-5.3311	0.7892	<0.0001	-5.4738	0.8125	<0.0001
Ln(AADT)	0.7864	0.0568	<0.0001	0.8114	0.0566	<0.0001	0.7832	0.0583	<0.0001
Length	0.5235	0.0255	<0.0001	0.5447	0.0251	<0.0001	0.5481	0.0253	<0.0001
Lane width	-0.0716	0.0521	0.1696	-0.0664	0.0524	0.2046	-0.0642	0.0539	0.2333
Shoulder width	-0.1518	0.0126	<0.0001	-0.1614	0.0130	<0.0001	-0.1692	0.0136	<0.0001
Curve (1: roadway with horizontal grade, 0: no)	0.4362	0.1651	0.0082	0.4660	0.1612	0.0038	0.4402	0.1637	0.0071
Dispersion	2.9189			2.5731			2.4397		
Log likelihood	-5556.0241			-4473.9065			-3793.1717		
AIC	11126.0482			8961.8129			7600.3435		

5.2.3 Crash Modification Factors

The CMFs for changes of lane and shoulder widths at non-curved and curved roadway segments for different crash severities were estimated using the cross-sectional method and presented in Table 5-8 and Table 5-9, respectively. It should be noted that segments with 12 ft lane width and 6 ft shoulder width were selected as base lines (i.e., CMF=1) based on the mean values from descriptive data statistics. The results from linear predictor show that the CMFs for changes of shoulder width consistently decrease as shoulder width increases. On the other hand, the results using the nonlinear predictor in GNM indicate that the CMFs for changes of lane width decrease until certain points (11.5 ft) and it increase after this point. The CMFs then start to decrease again after 12.5 ft of lane width. It was also found that increasing shoulder width is more effective to reduce severe crashes whereas increasing lane width is safety effective in reducing total crash frequency. Since both lane and shoulder widths interact with AADT, the CMFs for changes of lane and shoulder widths can be developed based on different AADT levels. Two ranges of AADT level (1000 to 5000 veh/day and 5001 to 36000 veh/day) were categorized and most frequent AADT levels were selected from each group to represent low and high traffic volumes. In Table 5-8 and Table 5-9, the CMFs were estimated for the selected two AADT levels (3000 and 15000 veh/day) to explore the variation of CMFs based on AADT changes. The results show that the CMFs for changes of lane and shoulder widths are more safety effective as AADT level increases. The results indicate that the CMFs for changes of lane width are lower for the roadways with narrower shoulder. Similarly, the results also show that the CMFs for changes of shoulder width are lower for the roadways with narrower lane. It should be mentioned that the CMFs for changes of lane and shoulder widths were adjusted by the interaction term for the roadways with horizontal curve.

Table 5-8: Evaluated CMFs for Non-Curved (Straight) Roadway Segment

(a) CMFs for changes of lane width

Changes of lane width	KABCO		KABC		KAB	
	CMF	S.E	CMF	S.E	CMF	S.E
AADT= 3,000						
12 to 10 ft	1.25	0.02	1.23	0.02	1.22	0.02
12 to 10.5 ft	1.18	0.01	1.17	0.01	1.16	0.01
12 to 11 ft	1.12	0.01	1.11	0.01	1.10	0.01
12 to 11.5 ft	0.93	0.01	0.93	0.01	0.93	0.01
Base: 12 ft	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	1.02	0.01	1.02	0.01	1.02	0.01
12 to 13 ft	0.63	0.02	0.65	0.02	0.66	0.02
12 to 13.5 ft	0.50	0.02	0.53	0.02	0.53	0.03
12 to 14 ft	0.39	0.02	0.42	0.03	0.43	0.03
AADT= 15,000						
12 to 10 ft	1.30	0.02	1.28	0.02	1.27	0.02
12 to 10.5 ft	1.22	0.01	1.20	0.01	1.19	0.01
12 to 11 ft	1.14	0.01	1.13	0.01	1.13	0.01
12 to 11.5 ft	0.92	0.01	0.92	0.01	0.92	0.01
Base: 12 ft	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	1.03	0.01	1.03	0.01	1.03	0.01
12 to 13 ft	0.57	0.02	0.60	0.02	0.60	0.02
12 to 13.5 ft	0.43	0.02	0.46	0.02	0.47	0.02
12 to 14 ft	0.32	0.02	0.36	0.02	0.37	0.02

Note: all CMFs are significant at a 95% confidence level

(b) CMFs for changes of shoulder width

Changes of shoulder width	KABCO		KABC		KAB	
	CMF	S.E	CMF	S.E	CMF	S.E
AADT= 3,000						
6 to 4 ft	1.36	0.01	1.38	0.01	1.39	0.01
6 to 4.5 ft	1.26	0.01	1.27	0.01	1.28	0.01
6 to 5 ft	1.17	0.01	1.18	0.01	1.18	0.01
6 to 5.5 ft	1.08	0.01	1.08	0.01	1.09	0.01
Base: 6 ft	1.00	-	1.00	-	1.00	-
6 to 6.5 ft	0.93	0.01	0.92	0.01	0.92	0.01
6 to 7 ft	0.86	0.01	0.85	0.01	0.85	0.01
6 to 7.5 ft	0.80	0.01	0.79	0.01	0.78	0.01
6 to 8 ft	0.74	0.01	0.73	0.01	0.72	0.01
AADT= 15,000						
6 to 4 ft	1.44	0.01	1.47	0.01	1.49	0.01
6 to 4.5 ft	1.32	0.01	1.34	0.01	1.35	0.01
6 to 5 ft	1.20	0.01	1.21	0.01	1.22	0.01
6 to 5.5 ft	1.10	0.01	1.10	0.01	1.10	0.01
Base: 6 ft	1.00	-	1.00	-	1.00	-
6 to 6.5 ft	0.91	0.01	0.91	0.01	0.91	0.01
6 to 7 ft	0.83	0.01	0.82	0.01	0.82	0.01
6 to 7.5 ft	0.76	0.01	0.75	0.01	0.74	0.01
6 to 8 ft	0.69	0.01	0.68	0.01	0.67	0.01

Note: all CMFs are significant at a 95% confidence level

Table 5-9: Evaluated CMFs for Roadway Segment with Horizontal Curve

(a) CMFs for changes of lane width

Changes of lane width		CMF (S.E)			CMF (S.E)			CMF (S.E)		
		KABCO	KABC	KAB	KABCO	KABC	KAB	KABCO	KABC	KAB
		Shoulder width= 4 ft			Shoulder width= 6 ft			Shoulder width= 8 ft		
		AADT= 3,000								
12 to 10 ft	CMF	1.18**	1.16**	1.16**	1.15**	1.13*	1.13*	1.12*	1.10	1.10
	S.E	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07
12 to 10.5 ft	CMF	1.13*	1.12*	1.12*	1.11*	1.10	1.10	1.09	1.07	1.07
	S.E	0.07	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07
12 to 11 ft	CMF	1.09	1.08	1.07	1.07	1.06	1.06	1.06	1.05	1.05
	S.E	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07
12 to 11.5 ft	CMF	0.92*	0.92*	0.92*	0.91**	0.91**	0.92*	0.91**	0.91	0.91*
	S.E	0.04	0.04	0.05	0.04	0.04	0.05	0.04	0.04	0.05
Base: 12 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
12 to 12.5 ft	CMF	1.04	1.04	1.03	1.05	1.05	1.04	1.05	1.05	1.05
	S.E	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
12 to 13 ft	CMF	0.65**	0.67**	0.67**	0.65**	0.68**	0.68**	0.66**	0.69**	0.69**
	S.E	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12 to 13.5 ft	CMF	0.52**	0.55**	0.55**	0.53**	0.56**	0.56**	0.54**	0.57**	0.57**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12 to 14 ft	CMF	0.42**	0.45**	0.45**	0.43**	0.46**	0.47**	0.44**	0.47**	0.48**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Shoulder width= 4 ft			Shoulder width= 6 ft			Shoulder width= 8 ft		
		AADT= 15,000								
12 to 10 ft	CMF	1.24**	1.21**	1.21**	1.20**	1.18**	1.18**	1.17**	1.15*	1.15*
	S.E	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.08
12 to 10.5 ft	CMF	1.17**	1.15**	1.15**	1.15**	1.13*	1.13*	1.13*	1.11	1.11
	S.E	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
12 to 11 ft	CMF	1.11*	1.10*	1.10	1.10*	1.08	1.08	1.08	1.07	1.07
	S.E	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07
12 to 11.5 ft	CMF	0.90**	0.91**	0.91*	0.90**	0.91**	0.91**	0.89**	0.89**	0.90**
	S.E	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Base: 12 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
12 to 12.5 ft	CMF	1.04	1.04	1.04	1.05	1.05	1.05	1.06	1.06	1.05
	S.E	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
12 to 13 ft	CMF	0.59**	0.61**	0.62**	0.60**	0.62**	0.63**	0.60**	0.63**	0.64**
	S.E	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12 to 13.5 ft	CMF	0.45**	0.48**	0.49**	0.46**	0.49**	0.50**	0.47**	0.50**	0.51**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12 to 14 ft	CMF	0.35**	0.38**	0.38**	0.35**	0.39**	0.39**	0.36**	0.40**	0.40**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

(b) CMFs for changes of shoulder width

Changes of lane width		CMF (S.E)			CMF (S.E)			CMF (S.E)		
		KABCO	KABC	KAB	KABCO	KABC	KAB	KABCO	KABC	KAB
		Lane width= 10 ft			Lane width= 12 ft			Lane width= 14 ft		
		AADT= 3,000								
6 to 4 ft	CMF	1.19**	1.20**	1.23**	1.16**	1.17**	1.20**	1.13**	1.13**	1.17**
	S.E	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
6 to 4.5 ft	CMF	1.14**	1.14**	1.17**	1.12**	1.12**	1.15**	1.10**	1.10**	1.12**
	S.E	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03
6 to 5 ft	CMF	1.09**	1.09**	1.11**	1.08**	1.08**	1.10**	1.06**	1.06**	1.08**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
6 to 5.5 ft	CMF	1.04	1.05*	1.05*	1.04	1.04	1.05*	1.03	1.03	1.04
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Base: 6 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
6 to 6.5 ft	CMF	0.96	0.96	0.95*	0.96	0.96	0.96	0.97	0.97	0.96
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7 ft	CMF	0.92**	0.91**	0.90**	0.93**	0.93**	0.91**	0.94**	0.94**	0.92**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7.5 ft	CMF	0.88**	0.87**	0.86**	0.90**	0.89**	0.87**	0.91**	0.91**	0.89**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 8 ft	CMF	0.84**	0.84**	0.81**	0.86**	0.86**	0.83**	0.89**	0.88**	0.85**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
		Lane width= 10 ft			Lane width= 12 ft			Lane width= 14 ft		
		AADT= 15,000								
6 to 4 ft	CMF	1.27**	1.28**	1.31**	1.23**	1.24**	1.28**	1.20**	1.21**	1.25**
	S.E	0.02	0.02	0.03	0.02	0.02	0.03	0.02	10.02	0.03
6 to 4.5 ft	CMF	1.19**	1.20**	1.23**	1.17**	1.18**	1.20**	1.15**	1.15**	1.18**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
6 to 5 ft	CMF	1.12**	1.13**	1.15**	1.11**	1.11**	1.13**	1.10**	1.10**	1.12**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 5.5 ft	CMF	1.06**	1.06**	1.07**	1.05*	1.06**	1.06**	1.05*	1.05*	1.06**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Base: 6 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
6 to 6.5 ft	CMF	0.94**	0.94**	0.93**	0.95*	0.95*	0.94**	0.96	0.95	0.95*
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7 ft	CMF	0.89**	0.88**	0.87**	0.90**	0.90**	0.88**	0.91**	0.91**	0.89**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7.5 ft	CMF	0.84**	0.83**	0.81**	0.85**	0.85**	0.83**	0.87**	0.87**	0.85**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 8 ft	CMF	0.79**	0.78**	0.76**	0.81**	0.80**	0.78**	0.83**	0.83**	0.80**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

5.2.4 Crash Modification Functions

In the cross-sectional method, the CMF is estimated using the coefficient of the variable associated with a specific roadway characteristic in the exponential functional form. Thus, CMFunctions can be summarized as shown in Table 5-10.

Table 5-10: Summary of Developed CMFunctions

Crash types	Non-curved segments		Curved segments	
	Changes of lane width (LW)	Changes of shoulder width (SW)	Changes of lane width (LW)	Changes of shoulder width (SW)
KABCO	$\exp\{0.1526 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{-0.0191 \times \ln(AADT) \times (SW - Base_{SW})\}$	$\exp[\{0.1526 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\} + \{0.0066(LW \times SW - Base_{LW} \times Base_{SW}\}]$	$\exp[\{-0.0191 \times \ln(AADT) \times (SW - Base_{SW})\} + \{0.0066(LW \times SW - Base_{LW} \times Base_{SW}\}]$
KABC	$\exp\{0.1414 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{-0.0201 \times \ln(AADT) \times (SW - Base_{SW})\}$	$\exp[\{0.1414 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\} + \{0.0071(LW \times SW - Base_{LW} \times Base_{SW}\}]$	$\exp[\{-0.0201 \times \ln(AADT) \times (SW - Base_{SW})\} + \{0.0071(LW \times SW - Base_{LW} \times Base_{SW}\}]$
KAB	$\exp\{0.1380 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{-0.0206 \times \ln(AADT) \times (SW - Base_{SW})\}$	$\exp[\{0.1380 \times \ln(AADT) \times (U_{LW} - Base_{U_{LW}})\} + \{0.0062(LW \times SW - Base_{LW} \times Base_{SW}\}]$	$\exp[\{-0.0206 \times \ln(AADT) \times (SW - Base_{SW})\} + \{0.0062(LW \times SW - Base_{LW} \times Base_{SW}\}]$

Figure 5-2 presents visualization of the variation of CMFs for changes of lane and shoulder widths at non-curved sections.

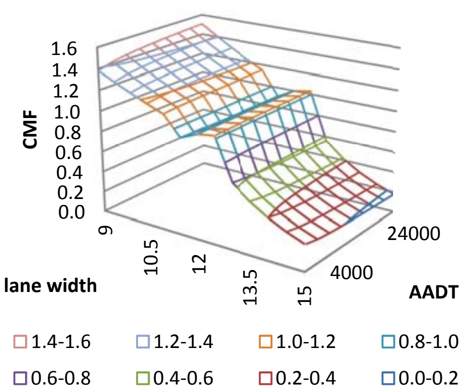
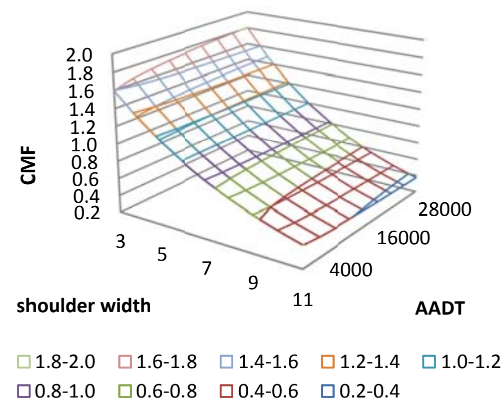
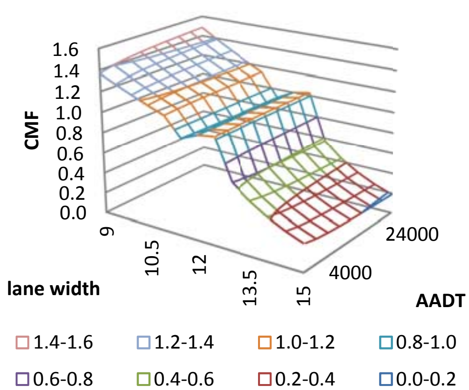
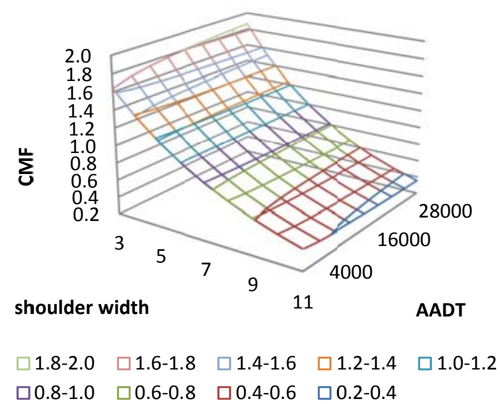
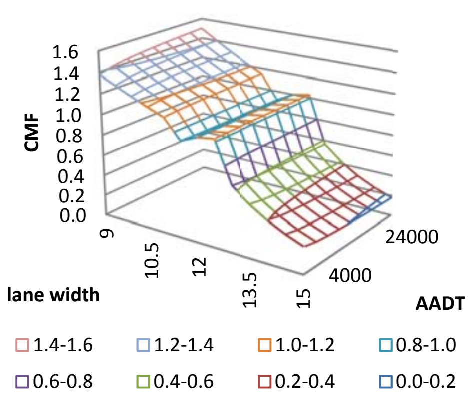
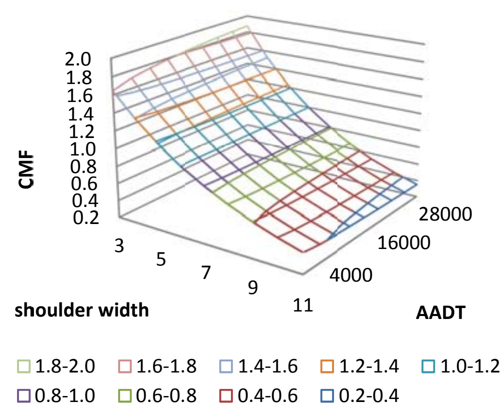
<table>
<tr><th>Crash type</th><th>CMFs (lane width × AADT)</th><th>CMFs (shoulder width × AADT)</th></tr>
<tr><td>KABCO</td><td>
</td><td>
</td></tr>
<tr><td>KABC</td><td>
</td><td>
</td></tr>
<tr><td>KAB</td><td>
</td><td>
</td></tr>
</table>

Figure 5-2: Visualization of CMFs for Straight Roadway Segment

5.3 Installation of Median Barriers on Rural Multilane Roadways

5.3.1 Generalized Linear Models

To calculate CMFs for the installation of median barriers on rural multilane roadways treatment using the cross-sectional method, Florida-specific SPFs for rural multilane roadways for different severities for All crashes were developed as presented in Table 5-11. In general, the estimated parameters are significant at 95% except one case (i.e., median barrier variable from KABCO model). Although the estimated parameter for median barrier for KABCO crashes is significant only at an 80% level, the CMF for KABCO crashes was estimated to be compared with CMF in the HSM.

Table 5-11: Estimated Parameters of GLMs for Different Severity Levels

	KABCO			KABC			KAB			KA		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-11.1497	2.0297	<0.0001	-10.7612	2.1063	<0.0001	-9.4289	2.2066	<0.0001	-8.4225	2.6152	0.0013
Median Barrier	-0.1272	0.0910	0.1622	-0.1979	0.0938	0.0348	-0.2669	0.0979	0.0064	-0.3422	0.1171	0.0035
Ln(AADT)	1.2045	0.1969	<0.0001	1.0803	0.2028	<0.0001	0.8618	0.2120	<0.0001	0.6573	0.2506	0.0087
Length	0.5528	0.0310	<0.0001	0.5362	0.0304	<0.0001	0.5209	0.0299	<0.0001	0.4637	0.0318	<0.0001
Max. Speed Limit	0.0115	0.0058	0.0497	0.0161	0.0062	0.0094	0.0233	0.0067	0.0005	0.0293	0.0083	0.0004
Dispersion	0.4802			0.4383			0.4027			0.3879		
Log likelihood	-1492.6748			-1243.4541			-1067.0366			-793.9592		
AIC	2997.3495			2498.9083			2146.0732			1599.9184		

5.3.2 Crash Modification Factors

Table 5-12 presents the estimated CMFs for the installation of median barriers on rural multilane roadways treatment. The results indicate that the CMFs for KAB and KA crashes are not included in the HSM. Thus, it can be recommended to adopt Florida-specific CMFs for KAB and KA severity levels. Since the standard errors of Florida-specific CMFs for KABCO and KABC crashes are higher than standard errors of CMFs in the HSM, it can be concluded that CMFs in the HSM are more reliable results. Lastly, the CMF for K crash in the HSM can also be used to estimate the safety effects.

Table 5-12: Estimated CMFs for Installation of Median Barriers

Crash type (Severity)	Road Type	Florida-specific			HSM		
		AADT	CMF	SE	AADT	CMF	SE
All (KABCO)	Rural multilane roadways	5,000 – 48,000	0.88*	0.08	20,000 – 60,000	1.24	0.03
All (KABC)			0.82	0.08		0.70	0.06
All (KAB)			0.77	0.07		N/A	N/A
All (KA)			0.71	0.08		N/A	N/A
All (K)			N/A	N/A		0.57	0.1

Note: All FL-specific CMFs are significant at a 95% confidence interval except one case
*: Not significant at a 90% confidence interval

5.4 Increasing Distance to Roadside Poles and Trees; Decreasing Density of Driveways and Roadside Poles on Rural Multilane Roadways

5.4.1 Generalized Linear Models

The GLMs with NB distribution for All (KABCO), All (KABC) and ROR (KABCO) crashes were developed as shown in Table 5-13. In general, the estimated parameters were statistically significant at a 90% confidence level. It was found that distance to poles was significant for All (KABCO), All (KABC) and ROR (KABCO) crashes whereas distance to trees was significant for All (KABCO) crashes only. The results indicated that the decrease of driveway density and decrease of poles density reduce crash frequency. The results also indicated that density of driveways has an interaction effect with AADT.

Table 5-13: Estimated Parameters of GLMs for Different Crash Types and Severity Levels

	All (KABCO) crashes			All (KABC) crashes			ROR (KABCO) crashes		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-10.2411	1.6393	<0.0001	-9.2788	1.5748	<0.0001	-17.0584	3.6675	<0.0001
Ln(AADT)	1.0127	0.1668	0.0032	0.8047	0.1650	<0.0001	1.4405	0.3880	0.0002
Driveway Density × Ln(AADT)	0.0024	0.0008	<0.0001	0.0021	0.0008	0.0071	0.0023	0.0013	0.0655
Poles Density	0.0194	0.0054	0.0003	0.0174	0.0052	0.0008	0.0194	0.0092	0.0355
Distance to Poles	-0.1471	0.0590	0.0127	-0.1107	0.0595	0.0628	-0.2496	0.1313	0.0572
Distance to Trees	-0.0288	0.0157	0.0672	-	-	-	-	-	-
Curve	1.0264	0.3168	0.0012	1.0185	0.3121	0.0011	1.0397	0.5070	0.0403
Dispersion	1.5000			1.1288			1.4532		
Log likelihood	-407.2575			-296.9135			-101.1665		
AIC	830.5149			607.8269			216.3331		

Florida-specific CMFs for the increasing the distance to roadside features and decreasing density of roadside elements on rural multi-lane roadways treatments are presented in Table 5-14. The results show that the increasing distance to roadside poles and trees reduce crash frequency. In particular, the CMFs for increasing distance to poles indicate that the treatment has higher safety effects in reducing ROR crashes than All crashes. Moreover, it was found that the decreasing density of driveways and roadside poles reduce crash frequency. In particular, the CMFs for decreasing density of driveways indicate that the treatment has higher safety effects in reducing total number of crashes. The results showed that the CMFs for decreasing density of driveways decrease as AADT level increases. The results also showed that decreasing density of roadside poles is more safety effective in reducing severe crashes.

Table 5-14: Developed CMFs

(a) Increasing Distance to Roadside Poles

Increasing Distance to Poles	All (KABCO) crashes	All (KABC) crashes	ROR (KABCO) crashes
	CMF (S.E)		
1 ft (Base)	1.00 (-)	1.00 (-)	1.00 (-)
2 ft	0.86 (0.05)	0.90 (0.05)	0.78 (0.10)
3 ft	0.75 (0.09)	0.80 (0.10)	0.61 (0.16)
4 ft	0.64 (0.11)	0.72 (0.13)	0.47 (0.19)
5 ft	0.56 (0.13)	0.64 (0.15)	0.37 (0.20)

Note: All CMF values are statistically significant at a 95% confidence level

(b) Increasing Distance to Roadside Trees

Increasing Distance to Trees	All (KABCO) crashes	
	CMF	S.E
1 ft (Base)	1.00	-
2 ft	0.97	0.02
3 ft	0.94	0.03
4 ft	0.92	0.04
5 ft	0.89	0.06

Note: All CMF values are statistically significant at a 90% confidence level

(c) Decreasing Density of Driveways

Driveways/mile	All (KABCO) crashes	All (KABC) crashes	All (KAB) crashes	ROR (KABCO) crashes
	CMF (S.E)			
AADT= 6000 veh/day				
70 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
60	0.81 (0.01)	0.83 (0.01)	0.86 (0.01)	0.82 (0.01)
50	0.66 (0.01)	0.69 (0.01)	0.73 (0.01)	0.67 (0.02)
40	0.53 (0.01)	0.58 (0.01)	0.63 (0.02)	0.55 (0.02)
30	0.43 (0.01)	0.48 (0.02)	0.54 (0.02)	0.45 (0.02)
AADT= 22000 veh/day				
70 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
60	0.79 (0.01)	0.81 (0.01)	0.84 (0.01)	0.79 (0.01)
50	0.62 (0.01)	0.66 (0.01)	0.70 (0.01)	0.63 (0.02)
40	0.49 (0.01)	0.53 (0.01)	0.58 (0.01)	0.50 (0.02)
30	0.38 (0.01)	0.43 (0.01)	0.49 (0.02)	0.40 (0.02)

Note: All CMF values are statistically significant at a 95% confidence level

(d) Decreasing Density of Roadside Poles

Poles/mile	All (KABCO) crashes	All (KABC) crashes	All (KAB) crashes	ROR (KABCO) crashes
	CMF (S.E)			
110 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
100	0.82 (0.04)	0.84 (0.04)	0.81 (0.05)	0.82 (0.07)
90	0.68 (0.07)	0.71 (0.07)	0.66 (0.08)	0.68 (0.13)
80	0.56 (0.09)	0.59 (0.09)	0.53 (0.09)	0.56 (0.16)
70	0.46 (0.10)	0.50 (0.10)	0.43 (0.10)	0.46 (0.17)

Note: All CMF values are statistically significant at a 95% confidence level

5.5 Decreasing School Zone Speed Limits on Segments in School Zone Area on Rural + Urban Roadways

5.5.1 Generalized Linear Models

Florida-specific SPFs were developed to predict crash frequency in a function of AADT, school zone speed limit and original speed limit of roadway segments for different severity levels for All crashes as shown in Table 5-15. Generally, the estimated parameters are significant at 90% confidence level.

Table 5-15: Estimated Parameters of GLMs for All Crashes

	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-9.5650	1.2464	<0.0001	-9.8365	1.3716	<0.0001	-8.6573	1.4142	<0.0001
School Zone Speed	0.0523	0.0188	0.0054	0.0567	0.0202	0.0050	0.0645	0.0212	0.0023
Ln(AADT)	1.1726	0.1232	<0.0001	1.1010	0.1354	<0.0001	0.9146	0.1383	<0.0001
Org. Speed Limit	-0.0349	0.0140	0.0127	-0.0281	0.0156	0.0710	-0.0305	0.0175	0.0819
Dispersion	1.7176			1.8554			1.7888		
Log likelihood	-605.2779			-476.3037			-65.0093		
AIC	1220.5557			962.6073			764.7753		

Florida-specific CMFs for the decreasing school zone speed limits on rural + urban roadways treatment were calculated as shown in Table 5-16. In general, Florida-specific CMFs show positive effects on road safety. In particular, the CMFs for severe crashes are lower than low severity levels. It should be noted that Florida-specific CMFs could not be compared with HSM since the CMF for decreasing school zone speed limits treatment is not available in the HSM.

Table 5-16: Developed CMFs for Decreasing School Zone Speed Limits

Road Type	AADT	School Zone Speed Limit	All (KABCO)		All (KABC)		All (KAB)	
			CMF	S.E	CMF	S.E	CMF	S.E
Urban / Rural Roadways	1,000 – 50,000	Base: 35mph	1.00	-	1.00	-	1.00	-
		30mph	0.77	0.02	0.75	0.02	0.72	0.02
		25mph	0.59	0.01	0.57	0.01	0.52	0.02
		20mph	0.46	0.01	0.43	0.01	0.38	0.01
		15mph	0.35	0.01	0.32	0.01	0.28	0.01

Note: All FL-specific CMFs are significant at a 95% confidence interval

5.6 Increasing Shoulder Width; Changing School Zone Speed Limits; Installation of Flashing Beacon at School Zone Signs; Decreasing Number of Driveways on Segments in School Zone Area on Urban Arterials

5.6.1 Generalized Linear Models

Nine Florida-specific full SPFs were developed using the NB model for different crash types and severity levels for school zone areas on urban arterials as shown in Table 5-17. In general, the results of nine full SPFs show that crash frequency increases for the school zone areas as traffic volume (i.e., AADT) and numbers of intersections increase. Moreover, the parameters for shoulder width, flashing beacon, school zone speed limit, and number of driveways were found to be significant for different full SPFs. It is worth to note that the crash frequency is higher for the school zone areas with bike lane for total (KABCO and KABC) and rear-end (KABCO) crashes whereas bike lane decreases non-motorized (KABCO) crashes. The may be because there is higher chance for the roadways with bike lane to have narrower lane width. Also, according to Sadek et al., (2007), drivers are more aware of bicyclists on the bike lane and drive more cautiously to avoid collision with bicyclists (e.g., deceleration suddenly, drive far from bicyclist, etc.). Hence, it can be expected to have more traffic conflicts and crashes (e.g., sideswipe, rear-end, etc.) when bike lane is installed on roadways with narrower lane width although bike lane can reduce bike-related crashes.

Table 5-17: Estimated Parameters of GLMs for Different Crash Types and Severities

(a) Total Crashes

	Total Crashes								
	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-6.9639	1.1470	<0.0001	-6.3045	1.2704	<0.0001	-7.9673	1.7650	<0.0001
Ln(AADT)	0.7396	0.1190	<0.0001	0.6425	0.1231	<0.0001	0.7130	0.1692	<0.0001
Length	2.5572	1.0647	0.0163	3.3464	1.0393	0.0013	4.4731	1.3706	0.0011
Shoulder Width	-	-	-	-0.0873	0.0399	0.0284	-0.0861	0.0548	0.1163
Number of Intersections	0.6530	0.1600	<0.0001	0.5287	0.1600	0.0009	0.3738	0.2075	0.0717
Bike Lane	0.5655	0.2494	0.0234	0.4501	0.2491	0.0708	-	-	-
Flashing Beacon	-	-	-	-0.3258	0.2189	0.1367	-0.4443	0.2760	0.1074
Dispersion	0.6763			0.3234			0.1123		
Log likelihood	-392.0432			-269.0250			-156.0081		
AIC	796.0865			554.0500			326.0163		

(b) Heavy Vehicle Crashes

	Heavy Vehicle Crashes								
	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-5.3787	1.3815	<0.0001	-3.7377	1.5739	0.0176	-5.7935	2.2497	0.0100
Ln(AADT)	0.5893	0.1517	0.0001	0.3284	0.1729	0.0575	0.4782	0.2450	0.0510
Number of Intersections	0.8638	0.1906	<0.0001	1.0152	0.2232	<0.0001	0.8130	0.3043	0.0075
Speed ≤ 20 mph	-0.5010	0.3217	0.1194	-0.7013	0.3569	0.0494	-0.7309	0.5101	0.1500
Dispersion	0.9243			0.5165			0.9077		
Log likelihood	-288.0782			-174.5390			-111.3530		
AIC	586.1565			359.0781			232.7060		

(c) Rear-end Crashes / Non-motorized Crashes

	Rear-end Crashes						Non-motorized Crashes		
	KABCO			KABC			KABCO		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-11.0608	1.9053	<0.0001	-13.4196	2.3169	<0.0001	-8.0995	3.0481	0.0079
Ln(AADT)	1.0166	0.1947	<0.0001	1.1845	0.2312	<0.0001	0.6043	0.3263	0.0640
Length	3.2864	1.7919	0.0666	3.9554	2.0233	0.0506	-	-	-
Number of Intersections	0.7368	0.2558	0.0040	0.6199	0.2930	0.0344	0.9275	0.4231	0.0284
Bike Lane	0.7687	0.3665	0.0359	-	-	-	-1.9431	1.1760	0.0985
Number of Driveways	-	-	-	-	-	-	0.2038	0.1200	0.0895
Dispersion	1.1950			0.9475			3.1386		
Log likelihood	-217.1037			-143.7820			-104.4357		
AIC	446.2074			297.5640			220.8714		

5.6.2 Crash Modification Factors

The CMFs for various roadway cross-section elements in school zone areas were estimated using the cross-sectional method. Table 5-18 presents the developed CMFs for changes of shoulder width for total (KABC and KAB) crashes. The results show that the CMFs decrease as shoulder width increases. The results also show that the safety effects are similar between KABC and KAB severity levels.

Table 5-18: Developed CMFs for Increasing Shoulder Width on Segments in School Zone Area

Increasing shoulder width	Total crashes			
	KABC		KAB	
	CMF	S.E	CMF	S.E
Base: no changes	1.000	-	1.000	-
Increasing 2ft	0.840	0.034	0.842	0.046
Increasing 4ft	0.705	0.028	0.709	0.039
Increasing 6ft	0.592	0.024	0.597	0.033
Increasing 8ft	0.497	0.020	0.502	0.028
Increasing 10ft	0.418	0.017	0.423	0.023

Note: all CMFs are significant at a 95% confidence level

The CMFs for installing flashing beacon at school zone signs were estimated for total (KABC and KAB) crashes as presented in Table 5-19. It was found that installation of flashing beacon is safety effective in reducing crashes. The safety effects of flashing beacon are higher for severe crashes (KAB) than injury crashes (KABC).

Table 5-19: Developed CMFs for Installation of Flashing Beacon at School Zone Signs on Segments in School Zone Area

Installing flashing beacons	Total crashes			
	KABC		KAB	
	CMF	S.E	CMF	S.E
	0.722*	0.150	0.641**	0.179

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

Table 5-20 shows the results of developed CMFs for decreasing maximum school zone speed limit for heavy vehicle crashes for different severity levels. In order to identify crashes related to heavy vehicles (e.g., heavy truck, bus, van, RV (recreational vehicle)), passenger vehicle related crashes (e.g., sedan, coupe, pickup, etc.) were excluded. The results indicate that decreasing maximum school zone speed limit ('25-35mph' to '15-20mph') has positive safety effects for heavy vehicle crashes. It is worth to mention that similar to the results of installing flashing beacon at school zone signs, the CMFs are lower for more severe heavy vehicle crashes.

Table 5-20: Developed CMFs for Changing School Zone Speed Limits on Segments in School Zone Area

Decreasing maximum school zone speed limit ('25-35mph' to '15-20mph')	Heavy vehicle crashes					
	KABCO		KABC		KAB	
	CMF	S.E	CMF	S.E	CMF	S.E
	0.606**	0.198	0.496**	0.129	0.481*	0.256

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

The CMFs for decreasing number of driveways in school zone areas were developed for non-motorized (pedestrian and bike related) crashes as presented in Table 5-21. The results show that the safety effects increase as number of driveways in school zone area decreases.

Table 5-21: Developed CMFs for Decreasing Number of Driveways in School Zone Area

Decreasing number of driveways	Non-motorized (pedestrian+bike) crashes	
	KABCO	
	CMF	S.E
Base: no changes	1.000	-
1 driveway	0.816*	0.098
2 driveways	0.665**	0.080
3 driveways	0.543**	0.065
4 driveways	0.443**	0.053

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

5.7 Widening Urban 4- to 6-lane Roadways

5.7.1 Safety Performance Functions

Table 5-22 presents the results of the full SPF models for the total number of crashes (KABCO) and fatal and injury crashes (KABC) per year. In order to estimate the full SPFs, crash data of both before and after periods for the reference sites were used with the time difference term. However, the variable of time difference was not significant which indicates that there is no significant difference between the before and after periods under no treatment condition. Moreover, the full SPFs were developed using the crash data for the before period and after periods separately. It was found that the full SPFs using the crash data for the after period show better model fitness than the model with the crash data of before period. Thus, in this study, the full SPFs were developed using the recent 4-year crash data (2009-2012), and all variables are significant at a 95% confidence level.

Table 5-22: Estimated Parameters of SPFs for Urban 4-Lane Roadways

	Coefficient					Dispersion (K)	Goodness of Fit	
	Intercept	Ln (AADT)	Segment Length	Shoulder Type	Median Width		Deviance	AIC
Crash Type	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)			
Total	-8.7362 (<0.0001)	1.0717 (<0.0001)	0.3443 (<0.0001)	-0.7047 (<0.0001)	-0.0142 (0.0119)	0.5214	187.1956	979.8421
Fatal + Injury	-8.3552 (<0.0001)	0.9767 (<0.0001)	0.3428 (<0.0001)	-0.5577 (0.0004)	-0.0168 (0.0030)	0.4043	182.2309	791.9376

5.7.2 Crash Modification Factors

The CMFs were estimated by the observational before-after analysis with EB method using Florida-specific full SPFs for total and injury crashes. The CMFs were also calculated for different roadway conditions over time. Table 5-23 presents the estimated CMFs using the observational before-after analysis with the EB method for total and injury crashes for different time periods. Generally, the safety effects of widening urban four-lane roadways to six-lane roadways were positive for both total and injury crashes. It is worth noting that the CMFs decrease over time until the third year after treatment. The differences between the safety effects of the third year and fourth year periods after the treatment are only 0.4% and 0.6% for total and injury crashes, respectively. This indicates that drivers are impacted by the change in roadway elements over time and that the safety impact might be consistent after certain time after treatment.

Table 5-23: Estimated CMFs of Widening Urban 4-Lane to 6-Lane Roadways by EB Method for Different Time Periods

		CMF (S.E)			
Crash Type	Time Periods	1st year after treated	2nd year after treated	3rd year after treated	4th year after treated
Total	One year term	0.901 (0.074)	0.847** (0.068)	0.798** (0.066)	0.802** (0.066)
	All years	0.850** (0.073)			
Fatal + Injury	One year term	0.841* (0.092)	0.755** (0.088)	0.696** (0.083)	0.702** (0.084)
	All years	0.761** (0.088)			

**: significant at a 95% confidence level, *: significant at a 90% confidence level

The CMFs estimated for the treated sites with different roadway characteristics (LOS changes and shoulder widths) are presented in Table 5-24. Since widening roadways can greatly change the roadway cross-sectional elements and the change is triggered mainly by operational issues, the LOS levels of each treated site in the periods before and after the treatment were determined and categorized into the three groups. Although the CMFs that are not significant at 90% confidence level may not represent statistically reliable safety effects of the treatment, it can be suggested to use these CMFs to check the general impact of widening of the four-lane roadway to six-lanes with relatively large variation. The results show that the safety effects are higher for roadway segments with low LOS level (high AADT per lane) in the period before the treatment and high LOS level (low AADT per lane) after. This may be because higher AADT per lane is significantly correlated with crash risk (Abdel-Aty and Radwan, 2000). It was also found that the CMFs are higher for shoulder widths less than or equal to 4 ft after treatment. Moreover, it is worth noting that the safety effects of conversion of urban four-lane roadways to six-lanes are higher for injury crashes than for total crashes (i.e., lower CMF).

Table 5-24: Estimated CMFs of Widening Urban 4-Lane to 6-Lane Roadways by EB Method for Different LOS Changes and Shoulder Widths

	LOS Changes in before and after periods						Shoulder Width in after period (ft)			
	LOS E of 4-lane → LOS C of 6-lane		LOS E of 4-lane → LOS D of 6-lane		LOS D of 4-lane → LOS D of 6-lane		≤ 4		≥ 6	
	53 Segments		37 Segments		48 Segments		38 Segments		100 Segments	
Crash Type	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
Total	0.809**	0.079	0.853*	0.100	0.918	0.096	0.916	0.098	0.737**	0.106
Fatal + Injury	0.657**	0.121	0.742*	0.157	0.868	0.175	0.807*	0.111	0.702**	0.147

**: significant at a 95% confidence level, *: significant at a 90% confidence level

5.7.3 Nonlinearizing Link Functions

In previous section, we found that the CMFs decrease over time until the third year after treatment. The differences between the safety effects of the third year and fourth year periods after treatment are only 0.4% and 0.6% for total and injury crashes, respectively. This indicates that drivers are impacted by the change in roadway elements over time and that the safety impact might be consistent after certain time after treatment. It was also found that the CMFs have variation based on different roadway characteristics (Level of Service (LOS) changes and shoulder widths).

The nonlinearizing link functions for total ($U_{yr(total)}$) and injury ($U_{yr(injury)}$) crashes were developed as shown in Figure 5-3 since the safety effects of widening urban four-lane roadways to six-lanes showed a nonlinear relationship with time after treatment (in Phase I). The relationship between the safety effects (ln(CMF)) and time trend (i.e., years after treatment) was plotted to determine the form of nonlinearizing link function. Nonlinear models with log form were assessed to estimate non-negative CMF value from the link functions. It was found that the observed CMFs initially decreased over time but it was consistent after certain amount of time after treatment for both total and injury crashes. Linear regression lines were also fitted but it did not reflect the nonlinear trend of CMFs over time clearly. Eleven nonlinear regression functions (Table 5-3) were compared to identify the best fitted function. The results show that double power and single power nonlinear functions were best fitted for total and injury crashes, respectively. It is worth noting that interaction effects between the CMFs and other explanatory variables were also investigated, but nonlinear effects were not found from any other parameters.

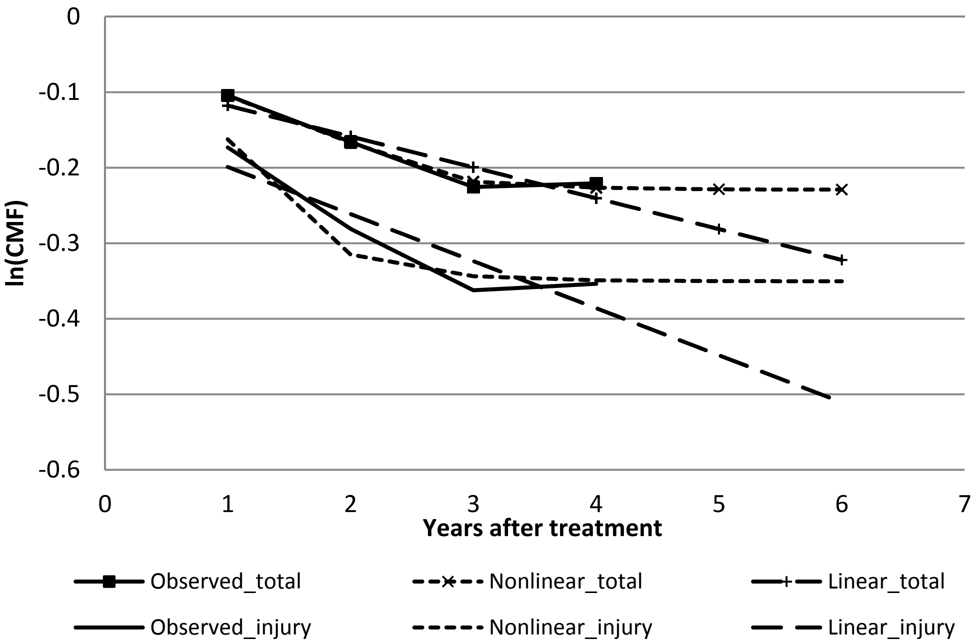


Figure 5-3: Nonlinearizing Link Functions in Different Time Periods

5.7.4 Crash Modification Functions

The CMFunctions for conversion of urban four-lane roadways to six-lanes were developed in order to identify the variation of CMFs with different multiple roadway characteristics. The CMFunctions with and without the nonlinearizing link function using Bayesian regression model were utilized to identify the advantages of using nonlinear predictors in analysis. Basically, the nonlinear predictors were used to reflect nonlinear relationship between the observed CMFs and time trend (i.e., years after treatment) in developing CMFunction with nonlinearizing link function. On the other hands, a continuous variable for time trend was used to evaluate the CMFunction without nonlinearizing link function. It is worth to note that the time trend was treated as a categorical variable with dummy variables in developing CMFunction. However, some variables were not significant at a 90% confidence level. Thus, it was not able to identify statistically significant nonlinear effect of changes of CMFs over time. Tables 5-25 and 5-26 present the developed CMFunctions with and without the nonlinear predictor for widening urban four-lane roadways to six-lane for total and injury crashes, respectively. To ensure that the CMF value from CMFunction cannot be negative estimate, log form of models were utilized. In general, both CMFunctions for total and injury crashes provide similar inferences. The CMFs decrease with a low LOS level (i.e., LOS E) before treatment as LOS level is higher afterwards when urban four-lane roadways are widened to provide an additional one through lane in each direction. However, the safety effects are relatively lower when the LOS levels of before and after periods are same. The results also show that narrowing shoulder width has negative safety effects on urban roadways. Moreover, it was found that narrowing median width has negative safety effects but the effects are smaller than narrowing the shoulder width for total crashes. On the other hand, there is no significant difference between the effects of narrowing shoulder width and narrowing median width for injury crashes. It can be recommended that for reducing total crashes, narrowing median width is preferable to make space for widening urban four-lane roadways than narrowing the shoulder width, if the roadways have to be widened and there is not enough right of way. It is worth noting that according to the CMFunction without the nonlinearizing link function, the CMFs decreased in value over time. However, the observed CMFs were consistent after certain amount of time after treatment based on the result of CMFunction with the nonlinear predictor. It is worth noting also that the effect of original shoulder width of treated sites was determined in CMFunctions for total crashes, whereas it was not identified in CMFunctions for injury crashes. The results show that the safety effects are higher as original shoulder width increases. According to the DIC (Deviance information criterion) guideline (Spiegelhalter et al., 2005), differences of more than 10 might rule out the model with the higher DIC value. Also, the differences of DIC value more than 5 and less than 10 generally can be used to identify reasonable improvement of model fit. Therefore, it can be concluded that using the nonlinearizing link function in developing CMFunctions can increase model fit significantly since the DIC values of the models with the nonlinear predictor for total and injury crashes are 9.07 and 6.37 lower than the models without the nonlinear predictor, respectively. All selected variables for both models are significant at 95%.

Table 5-25: Developed CMFunction by Bayesian Regression Method with and without Nonlinearizing Link Function for All Crashes

		CMFunction without Nonlinear predictor				CMFunction with Nonlinear predictor			
Variable		Estimate	SD	Interval 5.00%	Interval 95.00%	Estimate	SD	Interval 5.00%	Interval 95.00%
Intercept		0.0159	0.0208	-0.01839	0.05017	0.07742	0.02326	0.03893	0.1155
Years after treatment		-0.06086	0.005091	-0.06925	-0.05249	-	-	-	-
$U_{yr(total)}$ (Time Changes)		-	-	-	-	1.009	0.07904	0.8796	1.139
Narrowing Shoulder Width (1=Yes, 0=No)		0.1066	0.01858	0.07581	0.1373	0.1066	0.01818	0.07659	0.1364
Narrowing Median Width (1=Yes, 0=No)		0.02322	0.01211	0.003348	0.04318	0.02328	0.01189	0.003736	0.04279
LOS Changes Category (Base: LOS E to LOS D)	LOS D to LOS D	0.03756	0.008573	0.02348	0.05164	0.03748	0.008412	0.02358	0.05129
	LOS E to LOS C	-0.03357	0.008326	-0.04729	-0.01992	-0.0336	0.008199	-0.04712	-0.02022
Original Shoulder Width (ft)		-0.01809	0.002694	-0.02249	-0.01365	-0.0181	0.002634	-0.02244	-0.01375
DIC		-110.694				-119.767			

Table 5-26: Developed CMFunction by Bayesian Regression Method with and without Nonlinearizing Link Function for Fatal+Injury crashes

Variable		CMFunction without Nonlinear predictor				CMFunction with Nonlinear predictor			
		Estimate	SD	Interval 5.00%	Interval 95.00%	Estimate	SD	Interval 5.00%	Interval 95.00%
Intercept		-0.2224	0.02326	-0.2607	-0.1842	-0.09047	0.03393	-0.1463	-0.03485
Years after treatment		-0.05933	0.007427	-0.07152	-0.04712	-	-	-	-
$U_{yr(injury)}$ (Time Changes)		-	-	-	-	0.9579	0.1061	0.7836	1.133
Narrowing Shoulder Width (1=Yes, 0=No)		0.06487	0.02365	0.02576	0.1035	0.06492	0.02309	0.02699	0.103
Narrowing Median Width (1=Yes, 0=No)		0.06972	0.01755	0.04081	0.0985	0.06969	0.01713	0.04154	0.09782
LOS Changes Category (Base: LOS E to LOS D)	LOS D to LOS D	0.04709	0.0124	0.02672	0.06744	0.04708	0.01216	0.02715	0.06716
	LOS E to LOS C	-0.04563	0.01205	-0.06549	-0.02582	-0.04559	0.01179	-0.06499	-0.02623
DIC		-9.201				-15.575			

Table 5-27 presents a summary of equations for the developed CMFunctions with nonlinearizing link functions to estimate the CMFs of widening urban roadways with different additional treatments based on different LOS changes over time.

Table 5-27: Summary of CMFunction

		Combination of treatments			
Crash Type	LOS Changes	Widening urban roadways (WUR) only	WUR + Narrowing shoulder width (NSW)	WUR + Narrowing median width (NMW)	WUR + NSW + NMW
Total	LOS E to D	$\exp\{0.0774 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.184 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.1007 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.2073 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$
	LOS D to D	$\exp\{0.1149 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.2215 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.1382 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.2448 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$
	LOS E to C	$\exp\{0.0438 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.1504 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.0671 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$	$\exp\{0.1737 - 0.0181 * shld.width + 1.009 * U_{yr(total)}\}$
Injury	LOS E to D	$\exp\{-0.0905 + 0.9579 * U_{yr(injury)}\}$	$\exp\{-0.0256 + 0.9579 * U_{yr(injury)}\}$	$\exp\{-0.0208 + 0.9579 * U_{yr(injury)}\}$	$\exp\{0.0441 + 0.9579 * U_{yr(injury)}\}$
	LOS D to D	$\exp\{-0.0434 + 0.9579 * U_{yr(injury)}\}$	$\exp\{0.0215 + 0.9579 * U_{yr(injury)}\}$	$\exp\{0.0263 + 0.9579 * U_{yr(injury)}\}$	$\exp\{0.0912 + 0.9579 * U_{yr(injury)}\}$
	LOS E to C	$\exp\{-0.1361 + 0.9579 * U_{yr(injury)}\}$	$\exp\{-0.0712 + 0.9579 * U_{yr(injury)}\}$	$\exp\{-0.0664 + 0.9579 * U_{yr(injury)}\}$	$\exp\{-0.0015 + 0.9579 * U_{yr(injury)}\}$

5.8 Increasing Lane, Shoulder, Median, and Bike Lane Widths on Urban Arterials

5.8.1 Nonlinearizing Link Functions

The nonlinearizing link functions were developed to reflect the nonlinearity of lane and bike lane widths on crashes as shown in Figures 5-4 and 5-5, respectively. The relationships between the logarithm of crash rates (ln(CR)) and lane and bike lane widths were plotted to determine the form of the nonlinearizing link function (Lee et al., 2015). Crash rate was defined as the number of crashes per mile. It is worth noting that the interaction effects between the crash rates and other explanatory variables were also investigated, but it did not capture the nonlinear effects from any other parameters. A linear regression line was also fitted to the observed data but it does not reflect the nonlinearity of each predictor.

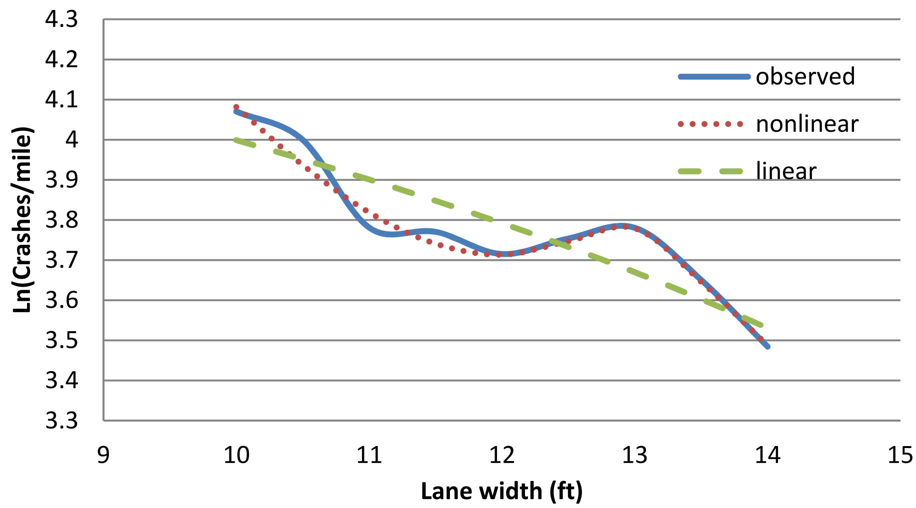


Figure 5-4: Development of Nonlinearizing Link Function for Lane Width

It was found that crash rates decrease as the lane width increases until 12 ft width and it increases as the lane width exceeds 12 ft. The crash rates start to decrease again after 13ft. The nonlinearizing link function for lane width (U_{LW}) is summarized as shown in Equation (5-2) as follow:

$$U_{LW}\begin{cases} = Ln(41.1 + 4.56(LaneWidth - 12)^2 & LaneWidth \leq 12 \\ = Ln(41.1 + 2.781(LaneWidth - 12) & 12 < LaneWidth \leq 13 \\ = Ln(43.9 - 11.24(LaneWidth - 13) & 13 < LaneWidth \end{cases} \tag{5-2}$$

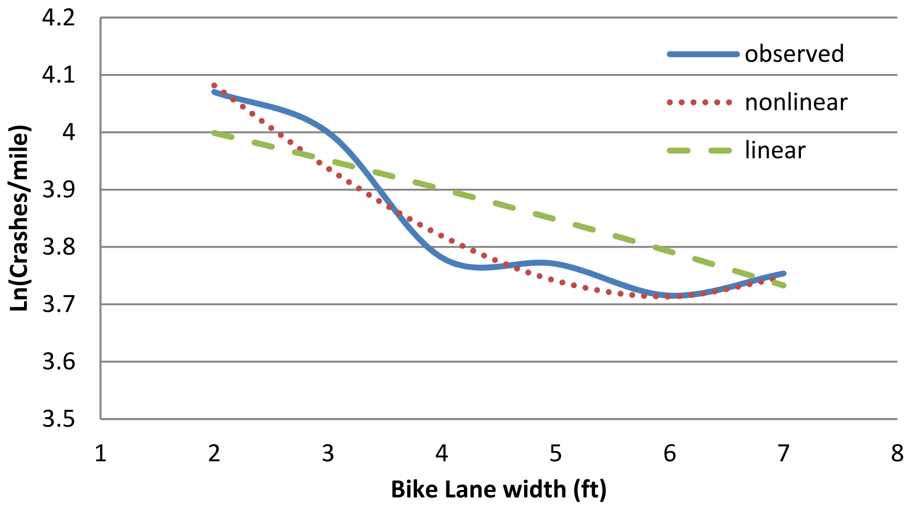


Figure 5-5: Development of Nonlinearizing Link Function for Bike Lane Width

The nonlinearizing link function for bike lane width (U_{BLW}) was developed as shown in Equation (5-3). It was found that crash rates decreases as the bike lane width increases until 6 ft width and it increases as the bike lane width exceeds 6 ft.

$$U_{BLW} = Ln(47.24 + 11.859(BikeLaneWidth - 7) + 3.7(BikeLaneWidth - 7)^2) \quad (5\text{-}3)$$

5.8.2 Generalized Nonlinear Models

The GNMs for different crash types and severities were developed using the nonlinearizing link functions (U_{LW} and U_{BLW}) as shown in Tables 5-28 and 5-29. In order to compare model performance, the GLMs were also developed. All the models fit the data well since the ratios of deviance to degrees of freedom are close to 1. In general, the estimated parameters were statistically significant at a 90% confidence level except in two cases (U_{LW} of GNM for All

(KABCO) crashes, categorical variable for lane width of GLM for All (KABCO) crashes). It was found that the GNMs generally provided better model fit (i.e., smaller AIC value) than the GLMs. This indicates that the inclusion of nonlinearizing link function improved the model fit. Although the AIC value from GLM is smaller than the GNM for All (KA) crashes, the GNM was selected for the evaluation of CMF since the effect of lane width was captured in the GNM. Although the continuous variable for lane width was significant for Bike crashes, it was not significant for All crashes. Thus, lane width was alternatively treated as categorical variable. However, the categorical variable was found to be significant only for All (KABCO) crashes.

As stated by Aarts and Van Schagen (2006) and Lee et al., (2015), lane width interacts with the relationship between speed and crash rate. Thus, an interaction term between lane width and posted speed limit was utilized in GLMs and GNMs. It was found that inclusion of the interaction term (Posted speed limit × U_{LW}) in GNM can improve the model fit. In order to obtain more reliable estimates, land use factor available in the RCI database was used. It is worth to note that the categorical variable for land use is significant for all models. In particular, the roadway segments in the central business district (CBD) area show the highest crash risk. The roadway segments in commercial areas have more crash frequency than residential areas. The results also show that the poor pavement condition decreases crash frequency. This might be because roadways with high-speed such as Interstate freeways and expressways were not included.

Table 5-28: Estimated Parameters of GLMs and GNMs for All Crashes

(a) NB (GLM)

Parameter		All (KABCO)			All (KABC)			All (KAB)			All (KA)		
		Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant		-13.7781	0.4250	<0.0001	-13.9171	0.3735	<0.0001	-13.2465	0.3780	<0.0001	-13.2653	0.4695	<0.0001
Ln(AADT)		1.4945	0.0348	<0.0001	1.3807	0.0339	<0.0001	1.2260	0.0346	<0.0001	1.0583	0.0426	<0.0001
Length		0.9624	0.0530	<0.0001	1.0494	0.0487	<0.0001	1.1129	0.0459	<0.0001	1.0864	0.0491	<0.0001
Median width		-0.0037	0.0015	0.0160	-0.0047	0.0016	0.0024	-0.0051	0.0015	0.0007	-0.0072	0.0018	0.0001
Posted speed limit		-	-	-	0.0150	0.0032	<0.0001	0.0167	0.0031	<0.0001	0.0341	0.0038	<0.0001
Lane width (Base: LW3)	LW1	0.3202	0.2071	0.1221	-	-	-	-	-	-	-	-	-
	LW2	0.2994	0.1947	0.1241	-	-	-	-	-	-	-	-	-
Pavement condition		0.0655	0.0284	0.0208	0.0948	0.0266	0.0004	0.1107	0.0260	<0.0001	0.0787	0.0307	0.0105
Land use (Base: Residen-tial)	CBD	0.5677	0.1405	<0.0001	0.6605	0.1308	<0.0001	0.6971	0.1262	<0.0001	0.7520	0.1436	<0.0001
	Commer-cial	0.3567	0.0380	<0.0001	0.4859	0.0355	<0.0001	0.5302	0.0352	<0.0001	0.5619	0.0430	<0.0001
Shoulder width		-0.0377	0.0071	<0.0001	-0.0365	0.0068	<0.0001	-0.0317	0.0068	<0.0001	-0.0346	0.0084	<0.0001
Dispersion		1.9999			1.5547			1.2801			1.2220		
Log likelihood		-21550.3636			-17543.5035			-13749.4693			-8351.7477		
AIC		43122.7271			35107.0070			27518.9386			16723.4955		

(b) GNM with U_{LW} and U_{BLW}

Parameter		All (KABCO)			All (KABC)			All (KAB)			All (KA)		
		Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant		-13.6287	0.3893	<0.0001	-13.9701	0.3730	<0.0001	-13.2770	0.3774	<0.0001	-13.2518	0.4695	<0.0001
Ln(AADT)		1.4916	0.0349	<0.0001	1.3818	0.0337	<0.0001	1.2257	0.0344	<0.0001	1.0583	0.0426	<0.0001
Length		0.9458	0.0536	<0.0001	1.0398	0.0485	<0.0001	1.1075	0.0457	<0.0001	1.0890	0.0492	<0.0001
Median width		-0.0048	0.0016	0.0030	-0.0051	0.0015	0.0008	-0.0054	0.0015	0.0003	-0.0064	0.0018	0.0004
Posted speed limit × U_{LW}		0.0013	0.0009	0.1381	0.0040	0.0008	<0.0001	0.0045	0.0008	<0.0001	0.0088	0.0010	<0.0001
Pavement condition		0.0622	0.0285	0.0293	0.0949	0.0265	0.0003	0.1094	0.0259	<0.0001	0.0800	0.0308	0.0093
Land use (Base: Residen-tial)	CBD	0.5876	0.1413	<0.0001	0.6532	0.1305	<0.0001	0.6993	0.1258	<0.0001	0.7566	0.1436	<0.0001
	Commer-cial	0.3546	0.0380	<0.0001	0.4866	0.0353	<0.0001	0.5319	0.0351	<0.0001	0.5621	0.0430	<0.0001
Shoulder width		-0.0394	0.0071	<0.0001	-0.0347	0.0067	<0.0001	-0.0302	0.0067	<0.0001	-0.0324	0.0084	<0.0001
U_{BLW}		0.0395	0.0154	0.0101	0.0892	0.0139	<0.0001	0.0824	0.0135	<0.0001	-	-	-
Dispersion		1.9979			1.5402			1.2683			1.2252		
Log likelihood		-21547.0554			-17522.3413			-13730.9572			-8355.3171		
AIC		43116.1107			35066.6825			27483.9144			16730.6342		

Table 5-29: Estimated Parameters of GLMs and GNMs for Bike Crashes

(a) NB (GLM)

		Bike (KABCO)			Bike (KABC)			Bike (KAB)		
Parameter		Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant		-10.4173	0.8373	<0.0001	-10.0473	0.8648	<0.0001	-9.9913	0.9691	<0.0001
Ln(AADT)		1.0625	0.0651	<0.0001	1.0001	0.0671	<0.0001	0.9456	0.0755	<0.0001
Length		1.1379	0.0676	<0.0001	1.1594	0.0696	<0.0001	1.1402	0.0737	<0.0001
Lane width		-0.0935	0.0433	0.0309	-0.1001	0.0452	0.0268	-0.1027	0.0510	0.0440
Median width		-0.0129	0.0029	<0.0001	-0.0119	0.0030	<0.0001	-0.0113	0.0034	0.0008
Posted speed limit		-0.0212	0.0056	0.0002	-0.0171	0.0058	0.0033	-0.0152	0.0066	0.0207
Land use (Base: Residen-tial)	CBD	0.7826	0.1954	<0.0001	0.8720	0.1998	<0.0001	0.8849	0.2252	<0.0001
	Commer-cial	0.5861	0.0634	<0.0001	0.6215	0.0664	<0.0001	0.6765	0.0761	<0.0001
Shoulder width		-0.0671	0.0128	<0.0001	-0.0678	0.0134	<0.0001	-0.0609	0.0152	<0.0001
Dispersion		1.7648			1.7774			1.7211		
Log likelihood		-4634.0787			-4298.2692			-3383.5683		
AIC		9288.1573			8616.5384			6787.1366		

(b) GNM with U_{LW} and U_{BLW}

		Bike (KABCO)			Bike (KABC)			Bike (KAB)		
Parameter		Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant		-14.2709	1.4157	<0.0001	-14.2105	1.4780	<0.0001	-13.9464	1.6738	<0.0001
Ln(AADT)		1.0682	0.0650	<0.0001	1.0043	0.0670	<0.0001	0.9495	0.0755	<0.0001
Length		1.1286	0.0670	<0.0001	1.1512	0.0690	<0.0001	1.1349	0.0731	<0.0001
Median width		-0.0143	0.0029	<0.0001	-0.0131	0.0030	<0.0001	-0.0127	0.0034	0.0002
U_{LW}		0.7131	0.3300	0.0307	0.7788	0.3438	0.0235	0.7170	0.3879	0.0646
Posted speed limit		-0.0212	0.0056	0.0001	-0.0172	0.0058	0.0030	-0.0152	0.0065	0.0198
Land use (Base: Residen-tial)	CBD	0.7565	0.1956	0.0001	0.8469	0.2000	<0.0001	0.8497	0.2255	0.0002
	Commer-cial	0.5766	0.0632	<0.0001	0.6118	0.0662	<0.0001	0.6630	0.0760	<0.0001
Shoulder width		-0.0673	0.0129	<0.0001	-0.0681	0.0135	<0.0001	-0.0618	0.0155	<0.0001
U_{BLW}		0.1172	0.0215	<0.0001	0.1155	0.0222	<0.0001	0.1201	0.0246	<0.0001
Dispersion		1.7240			1.7362			1.6780		
Log likelihood		-4619.6882			-4285.2646			-3372.6802		
AIC		9261.3765			8592.5291			6767.3605		

5.8.3 Crash Modification Factors

Tables 5-30 and 5-31 present the estimated CMFs of various roadway cross-section elements for All and Bike crashes, respectively. Note that segments with 10 ft lane width, 2 ft of bike lane width, 10 ft of median width, and 2 ft of shoulder width were selected as base lines (i.e., CMF=1). The CMFs from linear predictors show that the CMFs of changes in median and shoulder widths consistently decreased as their widths increased. On the other hand, the developed CMFs using the nonlinear predictors in GNMs indicate that the CMFs decreased until certain points (12 ft for lane width, 6 ft for bike lane width) and it increased after these points. For lane width, the CMFs start to decrease again after 13ft. For increasing lane width for All crashes, the CMFs were estimated based on different posted speed limits since the interaction term between posted speed limit and U_{LW} was significant in GNMs. The results show that changes of widths of roadway cross-section elements are more safety effective in reducing Bike crashes than All crashes. The results also show that there are no big difference between the CMFs for different severity levels for All and Bike crashes except increasing lane width for All crashes. It was found that increasing lane width is more safety effective to reduce severe crashes.

Table 5-30: Developed CMFs for All Crashes

(a) CMFs for increasing lane width

Lane width	All crashes			
	KABCO	KABC	KAB	KA
	CMF (S.E)			
Posted speed limit: 30 mph				
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
11 ft	0.990 (0.004)	0.969 (0.001)	0.965 (0.001)	0.933 (0.001)
12 ft	0.986 (0.005)	0.957 (0.001)	0.952 (0.001)	0.908 (0.001)
13 ft	0.988 (0.004)	0.964 (0.001)	0.960 (0.001)	0.923 (0.001)
14 ft	0.967 (0.004)	0.901 (0.001)	0.890 (0.001)	0.796 (0.001)
Posted speed limit: 40 mph				
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
11 ft	0.986 (0.005)	0.959 (0.001)	0.954 (0.001)	0.912 (0.001)
12 ft	0.981 (0.005)	0.943 (0.001)	0.936 (0.001)	0.879 (0.001)
13 ft	0.984 (0.005)	0.953 (0.001)	0.947 (0.001)	0.899 (0.001)
14 ft	0.956 (0.003)	0.871 (0.001)	0.856 (0.001)	0.737 (0.001)
Posted speed limit: 50 mph				
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
11 ft	0.983 (0.005)	0.949 (0.001)	0.943 (0.001)	0.891 (0.001)
12 ft	0.976 (0.005)	0.929 (0.001)	0.921 (0.001)	0.851 (0.001)
13 ft	0.981 (0.005)	0.941 (0.001)	0.934 (0.001)	0.876 (0.001)
14 ft	0.945 (0.002)	0.841 (0.001)	0.823 (0.001)	0.683 (0.001)

(b) CMFs for increasing bike lane width

Bike lane width	All crashes			
	KABCO	KABC	KAB	KA
	CMF (S.E)			
2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
3 ft	0.988 (0.005)	0.973 (0.004)	0.975 (0.004)	-
4 ft	0.977 (0.009)	0.949 (0.008)	0.953 (0.007)	-
5 ft	0.971 (0.011)	0.936 (0.010)	0.941 (0.009)	-
6 ft	0.972 (0.011)	0.938 (0.009)	0.942 (0.009)	-
7 ft	0.979 (0.008)	0.954 (0.007)	0.957 (0.007)	-

(c) CMFs for increasing median width

Median width	All crashes			
	KABCO	KABC	KAB	KA
	CMF (S.E)			
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
20 ft	0.953 (0.015)	0.950 (0.014)	0.947 (0.014)	0.938 (0.017)
30 ft	0.908 (0.029)	0.903 (0.027)	0.898 (0.027)	0.880 (0.032)
40 ft	0.866 (0.042)	0.858 (0.039)	0.850 (0.038)	0.825 (0.045)
50 ft	0.825 (0.053)	0.815 (0.049)	0.806 (0.048)	0.774 (0.056)

(d) CMFs for increasing shoulder width

Shoulder width	All crashes			
	KABCO	KABC	KAB	KA
	CMF (S.E)			
2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
4 ft	0.924 (0.013)	0.933 (0.013)	0.941 (0.013)	0.937 (0.016)
6 ft	0.854 (0.024)	0.870 (0.023)	0.886 (0.024)	0.878 (0.030)
8 ft	0.789 (0.034)	0.812 (0.033)	0.834 (0.034)	0.823 (0.042)
10 ft	0.730 (0.041)	0.758 (0.041)	0.785 (0.042)	0.772 (0.052)
12 ft	0.674 (0.048)	0.707 (0.047)	0.739 (0.050)	0.723 (0.061)

Note: all CMFs are significant at a 95% confidence level

Table 5-31: Developed CMFs for Bike Crashes

(a) CMFs for increasing lane width

Lane width	Bike crashes		
	KABCO	KABC	KAB
	CMF (S.E)		
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
11 ft	0.830 (0.072)	0.815 (0.074)	0.829 (0.084)
12 ft	0.770 (0.094)	0.751 (0.095)	0.768 (0.110)
13 ft	0.806 (0.072)	0.791 (0.074)	0.805 (0.084)
14 ft	0.539 (0.156)	0.510 (0.154)	0.538 (0.184)

(b) CMFs for increasing bike lane width

Bike lane width	Bike crashes		
	KABCO	KABC	KAB
	CMF (S.E)		
2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
3 ft	0.964 (0.006)	0.965 (0.007)	0.963 (0.007)
4 ft	0.934 (0.012)	0.935 (0.012)	0.933 (0.013)
5 ft	0.917 (0.015)	0.918 (0.015)	0.915 (0.017)
6 ft	0.919 (0.014)	0.920 (0.015)	0.917 (0.016)
7 ft	0.940 (0.011)	0.940 (0.011)	0.938 (0.012)

(c) CMFs for increasing median width

Median width	Bike crashes		
	KABCO	KABC	KAB
	CMF (S.E)		
10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
20 ft	0.867 (0.025)	0.877 (0.026)	0.881 (0.030)
30 ft	0.751 (0.032)	0.770 (0.046)	0.776 (0.053)
40 ft	0.651 (0.045)	0.675 (0.061)	0.683 (0.070)
50 ft	0.564 (0.056)	0.592 (0.071)	0.602 (0.082)

(d) CMFs for increasing shoulder width

Shoulder width	Bike crashes		
	KABCO	KABC	KAB
	CMF (S.E)		
2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
4 ft	0.874 (0.023)	0.873 (0.024)	0.884 (0.027)
6 ft	0.764 (0.039)	0.762 (0.041)	0.781 (0.048)
8 ft	0.668 (0.052)	0.665 (0.054)	0.690 (0.064)
10 ft	0.584 (0.060)	0.580 (0.063)	0.610 (0.076)
12 ft	0.510 (0.066)	0.506 (0.069)	0.539 (0.084)

Note: all CMFs are significant at a 95% confidence level

Table 5-32 presents a summary of the CMFunctions to estimate the CMFs of different treatments for different crash types and severities. As stated previously, in the cross-sectional method, the CMF is estimated using the coefficient of the variable associated with a specific roadway characteristic in the exponential functional form (i.e., CMFunction).

Table 5-32: Summary of CMFunctions

Crash types (Severities)	Increasing Lane Width (LW)	Increasing Bike Lane Width (BLW)	Increasing Median Width (MW)	Increasing Shoulder Width (SW)
All (KABCO)	$\exp\{0.0013 \times PSL \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.0395 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0048 \times (MW - Base_{MW})\}$	$\exp\{-0.0394 \times (SW - Base_{SW})\}$
All (KABC)	$\exp\{0.0040 \times PSL \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.0892 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0051 \times (MW - Base_{MW})\}$	$\exp\{-0.0347 \times (SW - Base_{SW})\}$
All (KAB)	$\exp\{0.0045 \times PSL \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.0824 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0054 \times (MW - Base_{MW})\}$	$\exp\{-0.0302 \times (SW - Base_{SW})\}$
All (KA)	$\exp\{0.0088 \times PSL \times (U_{LW} - Base_{U_{LW}})\}$	-	$\exp\{-0.0064 \times (MW - Base_{MW})\}$	$\exp\{-0.0324 \times (SW - Base_{SW})\}$
Bike (KABCO)	$\exp\{0.7131 \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.1172 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0143 \times (MW - Base_{MW})\}$	$\exp\{-0.0673 \times (SW - Base_{SW})\}$
Bike (KABC)	$\exp\{0.7788 \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.1155 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0131 \times (MW - Base_{MW})\}$	$\exp\{-0.0681 \times (SW - Base_{SW})\}$
Bike (KAB)	$\exp\{0.7170 \times (U_{LW} - Base_{U_{LW}})\}$	$\exp\{0.1201 \times (U_{BLW} - Base_{U_{BLW}})\}$	$\exp\{-0.0127 \times (MW - Base_{MW})\}$	$\exp\{-0.0618 \times (SW - Base_{SW})\}$

Note: PSL=Posted speed limit

5.9 Lane Reduction; Adding a Bike Lane + Lane Reduction on Urban Arterials

5.9.1 Crash Modification Factors

In order to estimate CMFs using the cross-sectional method, a NB regression model for urban roadways was estimated as shown in Table 5-33. The CMFs (in Table 5-34) for lane reduction and road diet (lane reduction + adding a bike lane) were calculated as $\exp(\beta_4)$ and $\exp(\beta_5)$. It is worth to mention that the analyses for KABC severity level and other crash type (e.g., bike crashes) were also performed but the results of NB regression models were not significant due to the low crash frequency. Therefore, the CMFs for lane reduction and road diet were calculated using cross-sectional method for All crashes (KABCO) only. The results showed that both lane reduction and road diet are safety effective in reducing crash frequency.

Table 5-33: NB Crash Prediction Model for Urban Arterials

	Coefficient						Dispersion (K)	Goodness of Fit	
	α Intercept	β_1 Ln(AADT)	β_2 Segment Length	β_3 Bike Lane	β_4 Lane Reduction	β_5 Road Diet		Deviance	AIC
Crash Type (Severity)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)			
All Crashes (KABCO)	-7.9851 (<0.0001)	1.0161 (<0.0001)	1.0006 (<0.0001)	-0.2473 (0.1489)	-0.6768 (<0.0001)	-0.8889 (0.0025)	1.7902	754.6141	3922

Table 5-34: Developed CMFs

Crash Type (Severity)	Lane Reduction		Road Diet (Bike Lane + Lane Reduction)	
All (KABCO)	0.51**	0.07	0.41**	0.12

**: significant at a 95% confidence level

5.10 Resurfacing Urban Arterials

5.10.1 Safety Performance Functions

Table 5-35 presents the results of the full SPF models for urban arterials for different severity levels. In order to estimate the full SPFs, crash data of both before and after periods for the reference sites were used with the time difference term. However, the variable of time difference was not significant which indicates that there is no significant difference between the before and after periods under no treatment condition. Three full SPFs were used in the EB method to estimate CMFs.

Table 5-35: Estimated Parameters of GLMs for Different Severity Levels

	KABCO			KABC			KAB		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-9.6912	1.3964	<0.0001	-10.5330	1.9268	<0.0001	-9.7964	2.1102	<0.0001
Ln(AADT)	1.1069	0.1545	<0.0001	1.0333	0.1863	<0.0001	0.8816	0.1943	<0.0001
Length	0.8547	0.1374	<0.0001	0.7741	0.1462	<0.0001	0.6686	0.1380	<0.0001
Speed Limit	-	-	-	0.0189	0.0119	0.1130	0.0317	0.0137	0.0209
Shoulder Width	-	-	-	-	-	-	-0.0836	0.0483	0.0834
Dispersion	1.4050			1.5256			1.3707		
Log likelihood	-442.7079			-334.1339			-261.0355		
AIC	893.4159			678.2679			534.0710		

5.10.2 Crash Modification Factors

The CMFs for resurfacing urban arterials treatment were developed using the observational before and after with CG and EB methods as shown in Table 5-36. It was found that for the KABCO and KABC severities, the results from CG method showed better estimates whereas the

CMF by EB method for KAB severity level has lower standard error value than the CG method. Based on the most reliable CMFs among two methods (i.e., lower standard error), the results indicated that the resurfacing treatment is more safety effective in reducing severe crashes.

Table 5-36: CMFs for Resurfacing Treatment on Urban Arterials using EB and CG Methods

Crash type (Severity)	Road Type	Florida-specific				
		AADT	EB		CG	
			CMF	SE	CMF	SE
All (KABCO)	Urban Arterials	2,100 - 40,500	0.997	0.042	**0.929***	0.040
All (KABC)			0.852**	0.052	**0.894****	0.050
All (KAB)			**0.858****	0.066	0.968	0.072

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval
Note: Values in bold denote the most reliable CMFs among before-after studies

Table 5-37 presents the estimated CMFs using the observational before-after analysis with CG method for total and injury crashes for different time periods. It is worth noting that the CMFs increase over time.

Table 5-37: Estimated CMFs for Different Time Periods for All Treated Sites

	CMFs by CG Method (S.E)			
Crash Type	1st year after treated	2nd year after treated	3rd year after treated	4th year after treated
All (KABCO)	0.766** (0.069)	0.853** (0.074)	1.023 (0.086)	1.153 (0.093)
All (KABC)	0.688** (0.087)	0.786** (0.098)	0.924 (0.108)	1.152 (0.127)

**: significant at a 95% confidence level, *: significant at a 90% confidence level

The CMFs were also calculated for different heavy vehicle volume rates using the CG method as shown in Table 5-38. The results showed that the resurfacing treatment is more safety effective for the roadways with higher heavy vehicle volume. Based on the results of CMFs over time for different heavy vehicle volume rates (in Table 5-39), it was found that the safety effects for the roadways with higher heavy vehicle volume are higher than the roadways with lower heavy vehicle volume until the third year after treatment. However, the opposite effects were found for fourth year period.

Table 5-38: Estimated CMFs for Different Heavy Vehicle Volume Rates

Crash type (Severity)	Road Type	Heave vehicle volume rate ≤ 3.3%		Heave vehicle volume rate > 3.3%	
		CMF	SE	CMF	SE
All (KABCO)	Urban Arterials	0.942	0.042	0.901**	0.050

**: Significant at a 95% confidence interval

Table 5-39: Estimated CMFs for Different Time Periods for Different Heavy Vehicle Volume Rates (for All (KABCO) Crashes)

	CMFs by CG Method (S.E)			
Heave vehicle volume rate	1st year after treated	2nd year after treated	3rd year after treated	4th year after treated
≤ 3.3%	0.806** (0.073)	0.899 (0.081)	1.051 (0.091)	1.124 (0.097)
> 3.3%	0.630** (0.098)	0.752** (0.090)	0.989 (0.096)	1.186 (0.119)

**: Significant at a 95% confidence interval

5.11 Adding Shoulder Rumble Strips on Freeways

5.11.1 Generalized Linear Models

In order to evaluate the CMF for the adding shoulder rumble strips on freeways treatment using the cross-sectional method, the GLMs with NB distribution were developed for different crash types and severities as shown in Table 5-40. In general, the estimated parameters were statistically significant at a 90% confidence level except the parameter for rumble strips in the model for ROR (KA) crashes.

Table 5-40: Estimated Parameters of GLMs for Different Crash Types and Severity Levels

(a) All crashes

	KABCO			KABC			KAB			KA		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-11.2554	0.4009	<0.0001	-11.3055	0.4106	<0.0001	-11.3506	0.4195	<0.0001	-10.8414	0.5532	<0.0001
Rumble Strips	-0.2607	0.0380	<0.0001	-0.2130	0.0379	<0.0001	-0.1384	0.0378	0.0003	-0.0832	0.0496	0.0936
Ln(AADT)	1.3305	0.0261	<0.0001	1.2686	0.0267	<0.0001	1.1336	0.0273	<0.0001	0.9478	0.0359	<0.0001
Length	0.7776	0.0204	<0.0001	0.7645	0.0200	<0.0001	0.7535	0.0195	<0.0001	0.7520	0.0233	<0.0001
Max. Speed Limit	-0.0065	0.0032	0.0414	-0.0080	0.0031	0.0103	0.0052	0.0031	0.0970	0.0121	0.0041	0.0032
Median Width	-0.0009	0.0004	0.0178	-	-	-	-	-	-	-	-	-
Dispersion	0.4088			0.3737			0.3314			0.4199		
Log likelihood	-9093.6958			-7547.5950			-6264.8815			-4444.9979		
AIC	18201.3916			15107.1900			12541.7631			8901.9957		

(b) ROR crashes

	KABCO			KABC			KAB			KA		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-9.8628	0.4870	<0.0001	-9.6452	0.5161	<0.0001	-9.6494	0.5744	<0.0001	-9.7365	0.8285	<0.0001
Rumble Strips	-0.1861	0.0443	<0.0001	-0.1432	0.0458	0.0017	-0.1305	0.0503	0.0095	-0.0625	0.0728	0.3904
Ln(AADT)	0.9516	0.0322	<0.0001	0.9033	0.0339	<0.0001	0.8223	0.0373	<0.0001	0.7086	0.0552	<0.0001
Length	0.7149	0.0228	<0.0001	0.6871	0.0223	<0.0001	0.6636	0.0230	<0.0001	0.6404	0.0282	<0.0001
Max. Speed Limit	0.0144	0.0038	0.0002	0.0095	0.0040	0.0175	0.0138	0.0043	0.0013	0.0139	0.0063	0.0280
Median Width	-0.0013	0.0005	0.0043	-0.0011	0.0005	0.0229	-	-	-	-	-	-
Dispersion	0.4919			0.4291			0.4079			0.4676		
Log likelihood	-6270.9001			-5095.1270			-4117.0950			-2513.3583		
AIC	12555.80002			10204.2541			8246.1901			5040.7165		

5.11.2 Crash Modification Factors

Based on the developed GLMs, Florida-specific CMFs for the Adding shoulder rumble strips on freeways treatment were evaluated and compared with CMFs in the HSM as presented in Table 5-41. It was not able to compare Florida-specific CMFs for All (KAB), All (KA), and ROR crashes with the HSM since the HSM does not contain the CMF values for those crash types.

In general, Florida-specific CMFs have higher safety effects than the CMFs in the HSM. Since the standard errors of Florida-specific CMFs are lower than standard errors of CMFs in the HSM, it can be concluded that Florida-specific CMFs are more reliable results. It is also worth to mention that the HSM does not specify traffic volume condition, whereas traffic volume of treatment is specified in the results of Florida-specific CMFs. The results show that rumble strips are effective in reducing both All and ROR crashes. In particular, the treatment is more safety effective for All crashes than ROR crashes. This may be because rumble strips are installed not only on outside shoulder but also on inside shoulder of the treated roadway segments. Moreover, the results indicate that safety effects of rumble strips are higher as severity level decreases (i.e., less severe crashes).

Table 5-41: CMFs for Adding Rumble Strips on Freeways

Crash type (Severity)	Road Type	Florida-specific			HSM		
		AADT	CMF	SE	AADT	CMF	SE
All (KABCO)	Freeway (Urban /Rural)	10,400-256,000	0.77**	0.03	Unspecified	0.82**	0.07
All (KABC)			0.81**	0.03		0.87	0.1
All (KAB)			0.87**	0.03		N/A	N/A
All (KA)			0.92*	0.05		N/A	N/A
ROR (KABCO)			0.83**	0.04		N/A	N/A
ROR (KABC)			0.87**	0.04		N/A	N/A
ROR (KAB)			0.88**	0.04		N/A	N/A

**: Significant at a 95% confidence interval *: Significant at a 90% confidence interval

5.12 Adding Lanes by Narrowing Existing Lane and Shoulder Widths on Freeways

5.12.1 Generalized Linear Models

Table 5-42 presents the developed Florida-specific SPFs for different severities for All crashes using NB models. The estimated parameters are significant at a 90% confidence level except two cases (i.e., constant of KABCO model and adding thru lane variable of KA model). It is worth to mention that the two parameters are significant at an 85% confidence level. Although the parameter for adding lanes by narrowing existing lanes and shoulders on freeways treatment is not even significant at an 85% for KAB crashes, the CMF was calculated to check the general safety effects of treatment.

Table 5-42: Estimated Parameters of GLMs for Different Severity Levels

	KABCO			KABC			KAB			KA		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-7.3256	5.0431	0.1463	-7.9798	4.7137	0.0905	-8.7007	4.2714	0.0417	-10.5396	5.0469	0.0368
Adding Thru Lane	0.4682	0.1526	0.0022	0.4510	0.1454	0.0019	0.1999	0.1472	0.1745	0.2326	0.1595	0.1447
Ln(AADT)	0.9248	0.4082	0.0235	0.9153	0.3816	0.0164	0.8869	0.3469	0.0106	0.9685	0.4092	0.0180
Length	1.9476	0.2925	<0.0001	1.9420	0.2761	<0.0001	1.9546	0.2591	<0.0001	1.7516	0.2777	<0.0001
Median Width	-0.0052	0.0019	0.0060	-0.0056	0.0019	0.0025	-0.0064	0.0020	0.0015	-0.0085	0.0031	0.0056
Dispersion	0.4370			0.3849			0.3086			0.3055		
Log likelihood	-510.1076			-435.9557			-355.7749			-246.0255		
AIC	1032.2151			883.9114			725.5499			504.0511		

5.12.2 Crash Modification Factors

Florida-specific CMFs for the adding lanes by narrowing existing lanes and shoulders on freeways treatment were evaluated and compared with CMFs in the HSM as shown in Table 5-43. It was not able to compare Florida-specific CMFs for KAB and KA crashes with the HSM since the HSM does not contain those CMF values.

The results indicate that after adding thru lane on freeways by narrowing existing lanes and shoulders, crash frequency will be increased. The results also show that the standard errors of FL-specific CMFs are higher than standard errors of CMFs in the HSM. Thus, it can be concluded that the CMFs for KABCO and KABC in the HSM are more reliable results. However, since the CMF for KABC in the HSM is not statistically significant, FL-specific CMF for KABC can be suggested to use. For KAB and KA crashes, FL-specific CMFs are not significant at a 90% confidence interval.

Table 5-43: Developed CMFs

Crash type (Severity)	Road Type	Florida-specific			HSM		
		AADT	CMF	SE	AADT	CMF	SE
All (KABCO)	Freeway (Urban)	140,000 – 300,000	1.60**	0.24	154,000 – 252,000	1.11**	0.05
All (KABC)			1.57**	0.22		1.11	0.08
All (KAB)			1.22	0.18		N/A	N/A
All (KA)			1.26	0.20		N/A	N/A

**: Significant at a 95% confidence interval

5.13 Installation of Roadside Barriers on Freeways

5.13.1 Safety Performance Functions

In order to estimate CMFs using the observational before-after with EB method, six full SPFs were developed by the NB model as shown in Table 5-44. Moreover, Table 5-45 presents the evaluated Bayesian Poisson-lognormal models for FB analyses along with the DIC results. In general, the results of the full SPFs and the developed Bayesian Poisson-lognormal models show that crash frequency is higher for the roadway segments with higher AADT and longer length. The results also show that the crash frequency is lower for the roadways with wider shoulder and median widths.

Table 5-44: Estimated Parameters of SPFs by NB Method for All and ROR Crashes

Crash Type	Severity	Intercept (p-value)	Segment length (p-value)	Log AADT (p-value)	Shoulder width (p-value)	Median width (p-value)	Maximum Speed (p-value)	Dispersion (k)	Deviance	AIC
All crashes	KABCO	-13.9584 (<0.0001)	1.6937 (<0.0001)	1.6798 (<0.0001)	-0.0360 (0.0304)	-0.0034 (0.0010)	-0.0364 (0.0014)	0.4408	716.4	4086.9
	KABC	-16.8558 (<0.0001)	1.6259 (<0.0001)	1.6796 (<0.0001)	-0.0405 (0.0237)	-0.0029 (0.0066)	-	0.4102	719.1	3448.7
	KAB	-14.9333 (<0.0001)	1.5983 (<0.0001)	1.4368 (<0.0001)	-0.0446 (0.0284)	-	-	0.3918	699.4	2760.6
ROR crashes	KABCO	-13.7554 (<0.0001)	1.3730 (<0.0001)	1.3902 (<0.0001)	-0.0915 (<0.0001)	-0.0039 (0.0756)	-	0.4697	705.7	2696.8
	KABC	-13.8629 (<0.0001)	1.3806 (<0.0001)	1.3738 (<0.0001)	-0.1013 (<0.0001)	-0.0044 (0.0013)	-	0.4345	683.0	2284.0
	KAB	-14.5482 (<0.0001)	1.4380 (<0.0001)	1.3503 (<0.0001)	-0.0932 (0.0004)	-	-	0.4341	646.5	1733.3

Table 5-45: Estimated Parameters of Bayesian Poisson-lognormal Models for All and ROR Crashes

(a) All crashes

	KABCO			KABC			KAB		
	Mean (S.D)	Interval 2.5%	Interval 97.5%	Mean (S.D)	Interval 2.5%	Interval 97.5%	Mean (S.D)	Interval 2.5%	Interval 97.5%
Intercept	-12.1 (3.223)	-17.38	-5.741	-14.87 (1.655)	-17.02	-10.63	-15.01 (1.328)	-17.72	-12.68
Log AADT	1.308 (0.275)	0.7634	1.747	1.496 (0.141)	1.154	1.685	1.428 (0.1164)	1.237	1.666
Segment length	1.388 (0.1079)	1.169	1.589	1.424 (0.08565)	1.255	1.592	1.449 (0.08938)	1.279	1.629
Shoulder width	-0.06071 (0.02325)	-0.1088	-0.02302	-0.0485 (0.01833)	-0.0847	-0.01362	-0.03811 (0.02091)	-0.07888	0.00386
Median width	-0.00376 (0.00151)	-0.00697	-0.00103	-0.00275 (0.00123)	-0.00531	-0.00044	-	-	-
Between-sites S.D (τ)	1.914 (0.2287)	1.44	2.33	2.374 (0.2171)	1.969	2.821	2.527 (0.2817)	2.016	3.126
DIC	3599.54			3155.17			2609.43		

(b) ROR crashes

	KABCO			KABC			KAB		
	Mean (S.D)	Interval 2.5%	Interval 97.5%	Mean (S.D)	Interval 2.5%	Interval 97.5%	Mean (S.D)	Interval 2.5%	Interval 97.5%
Intercept	-13.83 (0.8021)	-15.14	-12.0	-13.73 (1.165)	-15.49	-10.81	-14.28 (1.528)	-17.21	-11.49
Log AADT	1.373 (0.07084)	1.213	1.498	1.342 (0.09969)	1.089	1.492	1.307 (0.1342)	1.06	1.558
Segment length	1.301 (0.09071)	1.119	1.476	1.309 (0.09571)	1.126	1.5	1.358 (0.1069)	1.151	1.569
Shoulder width	-0.08455 (0.0225)	-0.1278	-0.04032	-0.09776 (0.02398)	-0.1453	-0.05139	-0.0886 (0.02675)	-0.1399	-0.0364
Median width	-0.00383 (0.00132)	-0.00642	-0.00122	-0.00441 (0.00142)	-0.00722	-0.00168	-	-	-
Between-sites S.D (τ)	2.167 (0.242)	1.733	2.682	2.358 (0.3032)	1.825	3.005	2.476 (0.4538)	1.743	3.512
DIC	2524.65			2180.12			1692.16		

S.D: Standard deviation

In order to identify the changes of CMFs, the full SPFs were developed for ROR crashes based on different vehicle, driver, weather, and time information as shown in Table 5-46. It should be noted that the CMFs with different information were calculated for ROR crashes only since roadside barriers were found to be more effective in reducing ROR crash frequency and severity than all crashes in the next section. Moreover, the EB method was conducted due to its better estimates for analysis of ROR crashes in the next section.

Table 5-46: Estimated Parameters of SPFs by NB Method for ROR Crashes with Different Information

Crash Type	Severity	Intercept (p-value)	Segment length (p-value)	Log AADT (p-value)	Shoulder width (p-value)	Median width (p-value)	Maximum Speed (p-value)	Curve (R/5730ft) (p-value)	Dispersion (k)	Deviance	AIC
ROR passenger vehicle crashes	KABCO	-19.3427 (<0.0001)	1.3188 (<0.0001)	1.6311 (<0.0001)	-0.0980 (<0.0001)	-0.0027 (0.0649)	0.0391 (0.0710)	0.1566 (0.0311)	0.5230	697.8	2392.4
	KABC	-24.3237 (<0.0001)	1.2537 (<0.0001)	1.7642 (<0.0001)	-0.0933 (0.0002)	-	0.0847 (0.0030)	-	0.4906	668.2	2005.9
	KAB	-26.3205 (<0.0001)	1.2697 (<0.0001)	1.7710 (<0.0001)	-0.0611 (0.0399)	-	0.0992 (0.0065)	-	0.4239	607.1	1471.9
ROR heavy vehicle crashes	KABCO	-11.3263 (<0.0001)	1.2216 (<0.0001)	1.0493 (<0.0001)	-0.0692 (0.0224)	-0.0072 (0.0002)	-	-	0.5076	600.9	1497.2
	KABC	-12.6849 (<0.0001)	1.3048 (<0.0001)	1.1699 (<0.0001)	-0.1129 (0.0011)	-0.0066 (0.0035)	-	-	0.5639	526.7	1217.6
	KAB	-24.9431 (0.0007)	1.1369 (<0.0001)	1.3792 (<0.0001)	-0.1845 (<0.0001)	-0.0053 (0.1030)	0.1513 (0.0185)	-	0.5658	423.4	841.3
ROR young age driver (15~24 years old) crashes	KABCO	-14.1884 (<0.0001)	1.1546 (<0.0001)	1.3293 (<0.0001)	-0.1049 (<0.0001)	-	-	-	0.2424	658.3	1629.5
	KABC	-26.8371 (<0.0001)	1.0761 (<0.0001)	1.6896 (<0.0001)	-0.1114 (<0.0001)	-	0.1264 (0.0010)	0.1630 (0.0817)	0.1758	608.7	1348.6
	KAB	-24.3044 (<0.0001)	1.0713 (<0.0001)	1.5270 (<0.0001)	-0.0903 (0.0091)	-0.0039 (0.1132)	0.1073 (0.0272)	-	0.1036	541.9	985.7
ROR middle age driver (25~64 years old) crashes	KABCO	-14.9349 (<0.0001)	1.3714 (<0.0001)	1.4501 (<0.0001)	-0.0885 (0.0003)	-0.0042 (0.0039)	-	-	0.5154	674.4	2204.8
	KABC	-22.2459 (<0.0001)	1.3210 (<0.0001)	1.6751 (<0.0001)	-0.0954 (0.0004)	-0.0039 (0.0212)	0.0682 (0.0189)	-	0.5265	630.0	1843.5
	KAB	-15.5379 (<0.0001)	1.4118 (<0.0001)	1.3861 (<0.0001)	-0.0856 (0.0101)	-	-	-	0.5887	561.7	1337.2
ROR old age driver (≥ 65 years old) crashes	KABCO	-21.3009 (<0.0001)	1.3154 (<0.0001)	1.7774 (<0.0001)	-	-0.0133 (0.0003)	-	0.4557 (0.0014)	0.8739	359.3	730.8
	KABC	-25.1901 (<0.0001)	1.5886 (<0.0001)	2.0357 (<0.0001)	-	-0.0094 (0.0530)	-	0.5391 (0.0038)	1.3116	244.8	475.7
	KAB	-30.3211 (<0.0001)	1.3519 (<0.0001)	2.4284 (<0.0001)	-	-	-	-	0.6200	192.5	308.3
ROR crashes in day time	KABCO	-13.8290 (<0.0001)	1.2474 (<0.0001)	1.3459 (<0.0001)	-0.0733 (0.0016)	-0.0030 (0.0293)	-	-	0.4836	700.5	2317.6
	KABC	-21.5279 (<0.0001)	1.2149 (<0.0001)	1.5952 (<0.0001)	-0.0766 (0.0018)	-	0.0676 (0.0085)	-	0.3973	659.9	1941.4
	KAB	-20.9055 (<0.0001)	1.1509 (<0.0001)	1.4021 (<0.0001)	-0.0471 (0.1067)	-	0.0767 (0.0173)	-	0.2364	622.3	1407.4
ROR crashes in night time	KABCO	-17.9102 (<0.0001)	1.4484 (<0.0001)	1.6618 (<0.0001)	-0.1108 (<0.0001)	-	-	-	0.5273	619.4	1672.5
	KABC	-22.4477 (<0.0001)	1.3075 (<0.0001)	1.7175 (<0.0001)	-0.1238 (<0.0001)	-0.0065 (0.0023)	0.0601 (0.1101)	-	0.3783	561.5	1315.9
	KAB	-20.7547 (<0.0001)	1.4888 (<0.0001)	1.8584 (<0.0001)	-0.1529 (<0.0001)	-	-	-	0.4710	464.6	959.7
ROR crashes in normal weather condition	KABCO	-19.5112 (<0.0001)	1.3168 (<0.0001)	1.4868 (<0.0001)	-0.0552 (0.0124)	-0.0055 (0.0002)	0.0584 (0.0098)	-	0.3625	685.7	2107.0
	KABC	-22.2356 (<0.0001)	1.3074 (<0.0001)	1.5724 (<0.0001)	-0.0683 (0.0054)	-0.0047 (0.0051)	0.0811 (0.0041)	-	0.3677	642.8	1781.8
	KAB	-25.5861 (<0.0001)	1.3186 (<0.0001)	1.6583 (<0.0001)	-0.0745 (0.0135)	-	0.1071 (0.0038)	-	0.4104	571.9	1392.0
ROR crashes in rain condition	KABCO	-16.6552 (<0.0001)	1.1959 (<0.0001)	1.5939 (<0.0001)	-0.1278 (<0.0001)	-	-	0.1491 (0.0763)	0.7166	633.2	1933.5
	KABC	-16.8452 (<0.0001)	1.1699 (<0.0001)	1.5809 (<0.0001)	-0.1329 (<0.0001)	-	-	-	0.6279	590.1	1556.8
	KAB	-15.3647 (<0.0001)	1.1892 (<0.0001)	1.3730 (<0.0001)	-0.1102 (0.0036)	-0.0047 (0.0583)	-	-	0.3730	500.2	995.6

5.13.2 Crash Modification Factors

The CMFs estimated for different crash types and severity levels using the EB and FB methods were presented in Table 5-47. It should be noted that the CMFs were estimated for all types of roadside barriers (i.e., w-beam guardrails + concrete barriers) and w-beam guardrails only. Due to the low sample size of treated sites with concrete barriers, it was not possible to calculate the CMFs for concrete barriers only. Generally, the safety effects of roadside barriers are positive and statistically significant for KAB severity level for both All and ROR crashes. The results show that roadside barriers are safety effective to reduce ROR (KABC) crashes whereas the CMFs are not statistically significant for All (KABC) crashes. Also, the estimated CMFs are statistically insignificant for KABCO except the CMF for w-beam guardrail from the EB method. The results show that the safety effectiveness of w-beam guardrails for All (KABCO) crashes is negative and this result is consistent with the HSM. This indicates that an addition of w-beam guardrails on roadside might increase crash frequency but reduce crash severity.

Overall, there are no big differences between the results of EB and FB methods. In particular, the standard errors of estimated CMFs by EB and FB methods are almost similar. This indicates that the results from the EB method are comparable to the FB method. It is worth to mention that for the CMFs for installation of W-bean guardrails only, the result from EB method produces slightly better estimates (i.e., lower standard error) for ROR crashes. This indicates that although the FB method has several statistical advantages over the EB approach, the EB method might show more reliable estimates when 1) sufficient sample size of reference sites was obtained and used to calculate full SPFs, and 2) there are enough crash frequencies for both treated and reference sites. FB might have been advantageous if the sample size was smaller.

Table 5-47: Evaluated CMFs for All and ROR Crashes using EB and FB Methods

Crash type	Severity	CMFs from the EB method				CMFs from the FB method			
		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
All crashes	KABCO	1.04	0.03	1.09**	0.03	1.01	0.03	1.06	0.03
	KABC	0.96	0.04	1.01	0.04	0.94	0.04	0.99	0.04
	KAB	0.82**	0.05	0.85**	0.05	0.82**	0.05	0.84*	0.05
ROR crashes	KABCO	0.95	0.05	1.01	0.05	0.93	0.05	1.01	0.06
	KABC	0.84**	0.06	0.88*	0.06	0.84**	0.06	0.89	0.07
	KAB	0.74**	0.07	0.75**	0.08	0.73**	0.07	0.74*	0.08

**: significant at 95% confidence level, *: significant at 90% confidence level

To determine the variation of CMFs with vehicle, driver, weather, and time information, the CMFs were estimated based on different vehicle size (passenger and heavy), driver age (young, middle, and old), weather condition (normal and rain), and time period (day time and night time). It is worth noting that numbers of categories for different factors were limited (2 to 3 categories for each condition) to insure enough crash frequency for each category.

Table 5-48 presents the estimated CMFs with different vehicle types. ROR crashes are categorized in two vehicle types which are passenger and heavy vehicles. Passenger vehicle is representing small cars such as sedan, coupe, etc. Heavy vehicle is including truck, bus, van, and recreational vehicles (RV). In general, roadside barriers were safety effective in reducing KAB crashes for both passenger and heavy vehicles. However, it is worth to mention that roadside barriers are more effective for heavy vehicles KAB crashes than passenger vehicles. Moreover, for KABC crashes, the CMFs for heavy vehicles are statistically significant and lower than the CMFs for passenger vehicle. The result also shows that an addition of w-beam guardrails can increase KABCO crashes for passenger vehicles.

Table 5-48: CMFs for ROR Crashes Using EB Method for Different Vehicle Types

Crash type	Severity	CMFs from the EB method			
		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	S.E	CMF	S.E
ROR passenger vehicle crashes	KABCO	1.03	0.08	1.15*	0.08
	KABC	0.92	0.08	0.98	0.09
	KAB	0.81*	0.10	0.81*	0.11
ROR heavy vehicle crashes	KABCO	0.90	0.08	0.93	0.09
	KABC	0.72**	0.10	0.75**	0.11
	KAB	0.66**	0.12	0.65**	0.13

**: significant at 95% confidence level, *: significant at 90% confidence level

The evaluated CMFs with different ranges of driver age are presented in Table 5-49. ROR crashes were divided into three driver age groups (young age: 15-24 years of age, middle age: 25-64 years of age, old age: 65 years of age and older). Although, most of estimated CMFs are not statistically significant, we can still check general variation of safety effects based on driver age groups. Generally, the safety effects of roadside barriers were positive for KABC and KAB crashes for middle and old age drivers. Moreover, it was found that w-beam guardrails are more safety effective to reduce KAB crashes for old age drivers than middle age drivers. It was also found that all CMFs for young age drivers were insignificant. The results indicate that installation of roadside barriers might not be safety effective for young age drivers. This may be because young age drivers tend to drive at higher speed than middle and old age drivers.

Table 5-49: CMFs for ROR Crashes Using EB Method for Different Ranges of Driver Age

Crash type	Severity	CMFs from the EB method			
		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	S.E	CMF	S.E
ROR young age driver (15~24 years old) crashes	KABCO	1.06	0.10	1.12	0.11
	KABC	1.06	0.14	1.11	0.15
	KAB	0.91	0.16	0.95	0.18
ROR middle age driver (25~64 years old) crashes	KABCO	0.93	0.06	1.05	0.08
	KABC	0.79**	0.07	0.85*	0.08
	KAB	0.69**	0.09	0.70**	0.10
ROR old age driver (more than 64 years old) crashes	KABCO	0.91	0.15	0.93	0.17
	KABC	0.80	0.23	0.80	0.25
	KAB	0.62	0.25	0.58*	0.25

**: significant at 95% confidence level, *: significant at 90% confidence level

Table 5-50 shows the estimated CMFs for ROR crashes in different weather conditions. ROR crashes in rain condition on roadways with wet surface were identified and grouped. Also, ROR crashes in normal weather condition on roadways with dry surface were grouped for the analysis. It is worth to note that ROR crashes in other weather conditions such as fog were excluded in the analysis. The results show that roadside barriers are more safety effective in reducing KAB crashes in the rain condition than the normal weather condition whereas the opposite was found for KABC crashes. In the rain condition, relatively more ROR crashes are expected due to the slippery roadway surface. Therefore, the safety effects for the possible injury (C) and property damage only (O) severity levels might be lower in the rain condition than normal weather condition since the barriers can also be perceived and considered as a roadside obstacle (Ben-Bassat and Shinar, 2011). However, for more severe ROR crashes, roadside barriers can prevent the serious impact between roadside hazard (e.g., trees, poles, ditch, etc.) and uncontrollable vehicle in slippery condition through colliding with energy absorbing barriers.

Table 5-50: CMFs for ROR Crashes Using EB Method for Different Weather Conditions

Crash type	Severity	CMFs from the EB method			
		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	S.E	CMF	S.E
ROR crashes in normal weather	KABCO	0.92	0.06	0.95	0.72
	KABC	0.82**	0.08	0.87	0.09
	KAB	0.76**	0.10	0.79*	0.11
ROR crashes in rain and wet surface condition	KABCO	0.92	0.08	1.12	0.09
	KABC	0.90	0.10	0.96	0.11
	KAB	0.75**	0.12	0.75*	0.13

**: significant at 95% confidence level, *: significant at 90% confidence level

The CMFs were estimated for ROR crashes based on time difference as show in Table 5-51. ROR crashes were categorized as day time and night time crashes using crash records in CARS. CARS data contains LGHT parameter and it provides the information of lighting condition for each crash record. It was found that roadside barriers are more effective to reduce KABC and KAB crashes in night time than day time. This may be because ROR crashes in night time tend to be more severe due to low visibility and high driving speed. Also, roadside barriers might be more helpful during night time to prevent impacts with roadside hazards.

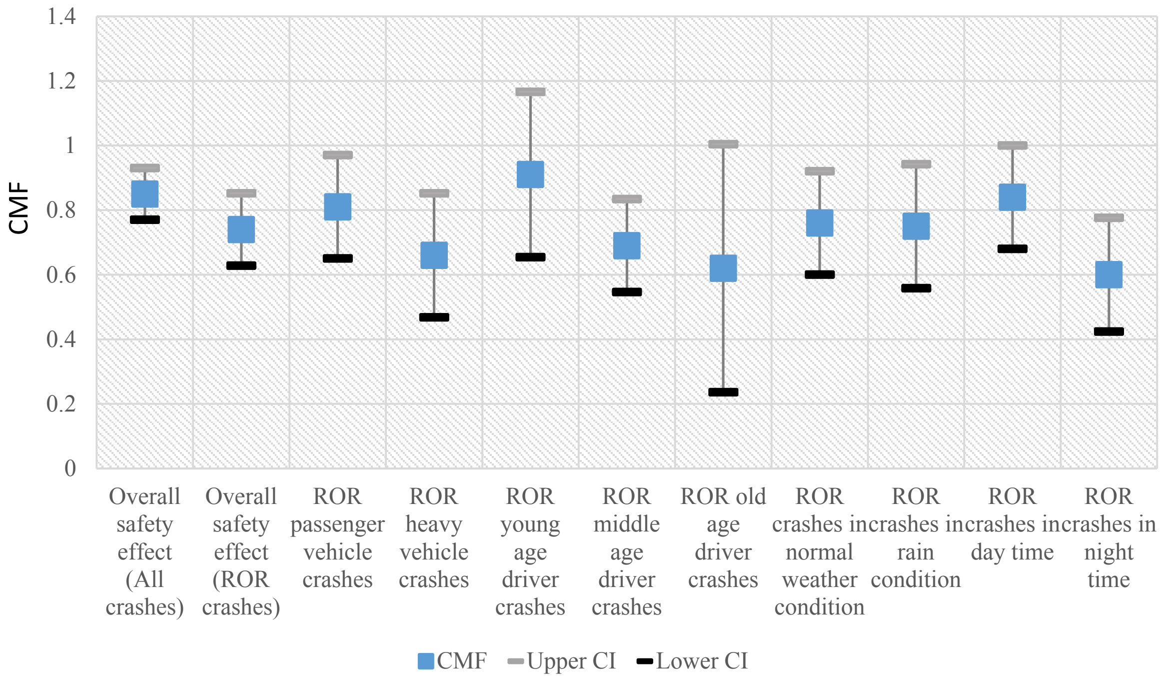
Table 5-51: CMFs for ROR Crashes Using EB Method for Different Time

Crash type	Severity	CMFs from the EB method			
		Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	S.E	CMF	S.E
ROR crashes in day time	KABCO	0.96	0.06	1.05	0.07
	KABC	0.94	0.08	1.01	0.09
	KAB	0.84*	0.10	0.89	0.12
ROR crashes in night time	KABCO	0.92	0.09	0.98	0.10
	KABC	0.71**	0.09	0.73**	0.10
	KAB	0.60**	0.11	0.53**	0.11

**: significant at 95% confidence level, *: significant at 90% confidence level

Figure 5-6 presents an example to visualize the estimated CMFs with 90% confidence interval for KAB severity level to easily compare the variation of CMFs with different crash types and crash information.

(a) Roadside barriers



(b) W-beam guardrails only

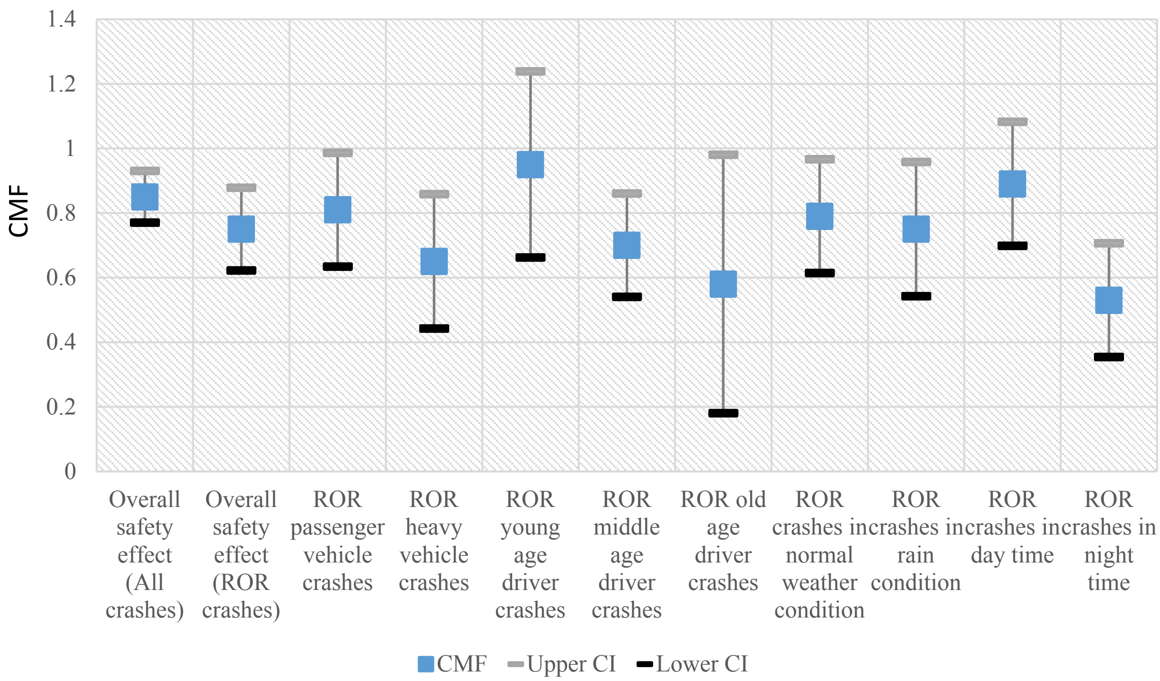


Figure 5-6: Development of Nonlinearizing Link Function

5.14 Increasing Shoulder Width; Installation of Roadside Barriers + Increasing Shoulder Width on Freeways

5.14.1 Generalized Linear Models

To estimate CMFs for 1) changing shoulder width and 2) installation of roadside barriers + changing shoulder width on roadway segments of freeways using the cross-sectional method, the NB models were developed as shown in Table 5-52. It should be noted that the estimated CMFs were significant only for All (KAB), ROR (KABC), and ROR (KAB) crashes.

Table 5-52: Estimated Parameters of SPFs by NB Method for All and ROR Crashes

	All (KAB) crashes			ROR (KABC) crashes			ROR (KAB) crashes		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-17.5543	1.3844	<0.0001	-16.4974	1.5197	<0.0001	-14.5294	1.8610	<0.0001
Segment length	1.4077	0.1118	<0.0001	1.3019	0.1226	<0.0001	1.0570	0.1068	<0.0001
Ln(AADT)	1.6528	0.1229	<0.0001	1.5639	0.1353	<0.0001	1.3111	0.1651	<0.0001
Shoulder width	-0.0358	0.0252	0.1547	-0.0588	0.0288	0.0001	-0.0550	0.0330	0.0284
Shoulder width×Roadside Barrier (1: yes, 0:no)	-0.0202	0.0093	0.0293	-0.0407	0.0107	0.0408	-0.0336	0.0130	0.0408
Dispersion	0.3303			0.4099			0.1417		
Deviance	471.3353			491.2167			436.0303		
AIC	1753.3			1611.4			1052.1		

5.14.2 Crash Modification Factors

Table 5-53 and Table 5-54 present the developed CMFs for changing shoulder width and installation of roadside barriers + changing shoulder width on freeways. The results showed that changing shoulder width with the installation of roadside barriers is more safety effective in reducing crashes than implementation of changing shoulder width only.

Table 5-53: Estimated CMFs for Changing Shoulder Width

Shoulder Width	All Crashes	ROR Crashes	
	KAB	KABC	KAB
	CMF (S.E)		
6 ft	1.15 (0.11)	1.27* (0.15)	1.25 (0.16)
10 ft (Base)	1.00	1.00	1.00
14 ft	0.86* (0.08)	0.79** (0.09)	0.80* (0.11)

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

Table 5-54: Estimated CMFs for Installation of Roadside Barriers + Changing Shoulder Width

Shoulder Width	All Crashes	ROR Crashes	
	KAB	KABC	KAB
	CMF (S.E)		
6 ft	1.25* (0.15)	1.49** (0.24)	1.43* (0.26)
10 ft (Base)	1.00	1.00	1.00
14 ft	0.80* (0.11)	0.67** (0.11)	0.70** (0.13)

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

CHAPTER 6. INTERSECTIONS AND SPECIAL FACILITIES

6.1 Converting a Minor-road Stop-Controlled Intersection to a Modern Roundabout

6.1.1 Safety Performance Functions

Due to data restriction, the construction date for the roundabout is not available. Therefore, cross-section analysis was been implemented to perform the analysis. We matched traffic crashes that occur within the intersection influence area. Six crash types were specified as follows:

1. Total Crashes (Total)
2. Fatality and Injury Crashes (F+I)
3. Single-Vehicle Crashes (Single)
4. Multi-Vehicle Crashes (Multiple)
5. Day-Time Crashes
6. Night-Time Crashes

These six crash types were modeled using negative binomial model. The result can be shown in Table 6-1. According to the model result shown in Table 6-1, three crash types are significant at least 90 percent level. These three crash types are fatality and injury crashes, single vehicle crashes, and multiple vehicle crashes. Other three crash type may include some potential trend but not significant at 90 percent level.

Table 6-1: Result of the SPFs

	Dependent variable					
	Total	F+I	Single	Multiple	Day	Night
	(1)	(2)	(3)	(4)	(5)	(6)
Log(Major ADT)	0.696***	0.689***	0.355**	0.792***	0.594***	0.836***
	(0.109)	(0.129)	(0.162)	(0.133)	(0.139)	(0.154)
Roundabout	-0.181	-0.322*	1.362***	-0.445**	-0.299	0.217
	(0.144)	(0.166)	(0.246)	(0.174)	(0.183)	(0.197)
Constant	-4.562***	-5.385***	-4.208***	-5.714***	-4.539***	-6.947***
	(0.915)	(1.090)	(1.375)	(1.117)	(1.169)	(1.305)
Observations	201	201	201	201	201	201
Log Likelihood	-476.996	-322.385	-226.589	-402.407	-332.713	-322.342
AIC	959.992	650.770	459.178	810.813	671.426	650.684

Note:*p<0.1; **p<0.05; *****p<0.01

6.1.2 Crash Modification Factors

The CMFs are shown in Table 6-2. In this table, three crash types are found to be significant in the NB models. F+I crashes is not significant at 90 percent level to decrease crashes but significant at 85 percent level. For single and multiple vehicle crashes, they are both significant at 90 percent. In fact, we can conclude that converting from an all-way stopped intersection to a modern roundabout decrease multiple crashes by 36%. Although the effects of day time and night time crashes are not significant in the NB models at the 90 percent level, it is also worth noting that the expected crashes may decrease during the day time and increase at night time after the conversion from all-way stop to modern roundabout.

Table 6-2: Developed CMFs

Setting (Road type)	Traffic Volume on the Major Road (AADT)	Crash Type (Severity)	CMF	S.E.
Rural +Urban	700 to 24,500	All types (KABCO)	0.83	0.12
		All types (KABC)	0.75*	0.16
		Multiple (KABCO)	0.64*	0.11
		Day Time (KABCO)	0.74	0.14
		Night Time (KABCO)	1.24	0.25

*: significant at a 90% confidence interval

6.2 Adding Right Turn Lane

6.2.1 Safety Performance Functions

In order to estimate CMFs using the cross-sectional method, a NB regression model for rural intersections were estimated as shown in Table 6-3. All variables are significant at a 99% confidence level. In general, the results of the SPFs show that crash frequency are higher for the roadway segments with higher entering AADT. However, the crash frequency increases as numbers of approach with right lane installed. In fact this result is the same a study published in Transportation Research Board 2016 (Himes et al., 2016) which indicate an increasing trend for installing right turn lane at non-signalized rural intersections in the NB models.

Table 6-3: NB Regression Models for Rural Intersections

<table>
<tr><th rowspan="4">Crash Type</th><th colspan="3">Coefficient</th><th rowspan="4">Dispersion (K)</th><th colspan="2">Goodness of Fit</th></tr>
<tr><th>α</th><th>β_1</th><th>β_2</th><th rowspan="3">Deviance</th><th rowspan="3">AIC</th></tr>
<tr><th>Intercept</th><th>Ln (Entering AADT)</th><th>Numbers of Approach with Right Turn Lanes</th></tr>
<tr><th>Estimate (P-Value)</th><th>Estimate (P-Value)</th><th>Estimate (P-Value)</th></tr>
<tr><td rowspan="2">KABCO</td><td>-6.387</td><td>1.0172</td><td>0.2543</td><td rowspan="2">0.4174</td><td rowspan="2">301.03</td><td rowspan="2">1566.6</td></tr>
<tr><td><0.0001</td><td><0.0001</td><td>0.0005</td></tr>
<tr><td rowspan="2">KABC</td><td>-6.0903</td><td>0.9063</td><td>0.3927</td><td rowspan="2">0.4239</td><td rowspan="2">304.63</td><td rowspan="2">1361.6</td></tr>
<tr><td><0.0001</td><td><0.0001</td><td>0.0005</td></tr>
</table>

6.2.2 Crash Modification Factors

The FL-specific CMFs (in Table 6-4) for installing exclusive right turn lane at 1 approach were also calculated. However comparing the results with the CMFs presented in HSM, we found the standard error is lower for both KABCO and KABC crashes. Therefore, we believe it is better to use the CMFs in HSM. In conclusion, we suggests that installing exclusive right turn lane at 1 approach reduce the KABCO crashes by 4 percent and reduce KABC crashes by 9 percent.

Table 6-4: CMF for Installing Exclusive Right Turn Lane at 3-legged Signalized Intersections

Treatment	CMF Source	Traffic Volume on the Major Road (AADT)	Traffic Volume on the Minor Road (AADT)	Crash Type (Severity)	CMF	S.E.
Install Exclusive Right Turn Lane at 1 Approach	HSM	7,200 to 55,100	550 to 8,400	All Type (KABCO)	0.96*	0.02
				All Type (KABC)	0.91*	0.04
	FL	2,725 to 29,500	170 to 15,400	All Type (KABCO)	1.29*	0.09
				All Type (KABC)	1.48*	0.11

*: significant at a 90% confidence interval

6.3 Adding Left Turn Lane

6.3.1 Crash Modification Factors

We estimate the effect of installing left turn lanes on major and minor roads. Nine crash types are examined with independent variables shown as follows:

1. AADT of the major road
2. AADT of the minor road
3. Existence of exclusive left turn lane on the major road
4. Existence of exclusive left turn lane on the minor road
5. Existence of exclusive right turn lane on the major road

6. Existence of exclusive right turn lane on the minor road

7. Median Width on the major road

8. Median Width on the minor road

As shown in Table 6-5, the result is for installing exclusive left turn lane on the major road. However none of the crash types are found significantly influence traffic crashes.

Table 6-5: CMF for Installing Exclusive Left Turn Lane on the Major Road

Treatment	Setting (Road type)	Traffic Volume on the Major Road (AADT)	Traffic Volume on the Minor Road (AADT)	Crash Type (Severity)	CMF	S.E.
Install Exclusive Left Turn Lane on the Major Road	Rural	2,725 to 29,500	170 to 15,400	All types (KABCO)	0.93	0.17
				All types (KABC)	0.91	0.17
				All types (KAB)	1.07	0.22
				Single (KABCO)	0.72	0.20
				Multiple (KABCO)	1.04	0.19
				Day Time (KABCO)	0.96	0.18
				Night Time (KABCO)	0.85	0.19
				Rear-End (KABCO)	0.84	0.17
				Angle+Left Turn (KABCO)	1.09	0.24

Note: all CMF values are not significant at a 90% confidence level

As shown in Table 6-6, the result is only significant for single vehicle crashes when installing exclusive left turn lane on the minor road. It is expected to see a 32% crash reduction for single vehicle crashes. However, other crash types are not significant at 90 percent level. Table 6-7 presents the NB regression model for single vehicle crashes.

Table 6-6: CMF for Installing Exclusive Left Turn Lane on the Minor Road

Treatment	Setting (Road type)	Traffic Volume on the Major Road (AADT)	Traffic Volume on the Minor Road (AADT)	Crash Type (Severity)	CMF	S.E.
Install Exclusive Left Turn Lane on the Minor Road	Rural	2,725 to 29,500	170 to 15,400	All types (KABCO)	0.87	0.10
				All types (KABC)	0.94	0.11
				All types (KAB)	1.02	0.12
				Single* (KABCO)	0.68	0.12
				Multiple (KABCO)	0.92	0.11
				Day Time (KABCO)	0.88	0.11
				Night Time (KABCO)	0.93	0.12
				Rear-End (KABCO)	0.82	0.11
				Angle+Left Turn (KABCO)	0.97	0.13

*: significant at a 90% confidence level

Table 6-7: SPF Model for Single Vehicle Crashes

	Single (KABCO) crashes		
Parameter	Coeffi-cient	SE	p-value
Constant	-6.8004	1.6688	<0.0001
Ln(Major AADT)	0.5293	0.1900	0.005
Ln(Minor AADT)	0.3893	0.1278	0.002
Minor Exclusive Left-Turn Lane	-0.3822	0.1706	0.025
Minor Exclusive Right-Turn Lane	0.3554	0.1656	0.318
Major Isolated Right Turn Lane	0.4785	0.1861	0.010
Major Median Width	0.01287	0.0067	0.055
Dispersion	0.7124		
Deviance	245.04		
AIC	910.87		

6.4 Changes of Median Width at Signalized Intersection

6.4.1 Crash Modification Factors

After we prepared the data, we conducted cross-sectional studies to see if the investigate whether the width has a significant influence on roadway crashes. In order to get in-depth results for each crash categories, we checked the significance for nine crash types including KABCO, KABC, KAB, single vehicle, multiple vehicle, daytime, night time, rear end, and angle+left turn crashes. Each crash type is examined for median width on the major road. For increasing median width on the major road, only CMF for single vehicle is significant. On the other hand, for increasing median width on the minor road, KABC and KAB crashes are significant.

Table 6-8 presents the estimated CMFs for widening median width on major road at rural signalized intersections. The CMFs were developed based on the SPF in Table 6-7. The CMFs on the minor road for the different severities were evaluated as shown in Table 6-9.

Table 6-8: CMF for Widening the Median on Major Road at Rural Signalized Intersections

Crash Type	Crash Severity	Width	Rural Signalized Intersection
			Widening median on the major road
Single	KABCO	0 (base)	1 (-)
		10	1.137 (0.007)
		20	1.294 (0.136)
		30	1.471 (0.205)
		40	1.674 (0.275)

Table 6-9: CMF for Widening the Median on Minor Road at Rural Signalized Intersections

Crash Type	Crash Severity	Width	Rural Signalized Intersection
			Widening median on the minor road
All Types	KABC	0 (base)	1 (-)
		2	0.983 (0.011)
		4	0.966 (0.022)
		6	0.949 (0.034)
		8	0.933 (0.045)
		10	0.917 (0.056)
All Types	KAB	0 (base)	1 (-)
		2	0.977 (0.012)
		4	0.954 (0.023)
		6	0.932 (0.035)
		8	0.911 (0.047)
		10	0.890 (0.058)

Table 6-10 presents the developed GLMs for all types of crashes, respectively.

Table 6-10: NB Model for All Crashes

	All Types (KABC) crashes			All Types (KAB) crashes		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-5.2026	1.0882	<0.0001	-4.3092	1.1145	<0.0001
Ln(Major AADT)	0.6229	0.1176	<0.0001	0.5292	0.1204	<0.0001
Ln(Minor AADT)	0.2465	0.0856	0.004	0.1642	0.0875	0.061
Major Exclusive Right-Turn Lane	0.3921	0.1228	0.001	0.4843	0.1262	<0.0001
Minor Exclusive Right-Turn Lane	0.3409	0.111	0.002	0.397	0.1132	<0.0001
Major Isolated Right Turn Lane	0.3357	0.1434	0.019	0.4039	0.1441	0.005
Minor Median Width	-0.0117	0.0059	0.048	-0.0114	0.006	0.057
Dispersion	0.409567497			0.392618767		
Deviance	313.69			304.3		
AIC	1364.8			1179.6		

6.4.2 Crash Modification Functions

Table 6-11 provides a summary of the developed CMFunctions for widening median width at rural signalized intersections.

Table 6-11: CMFunctions for Widening the Median at Rural Signalized Intersections

Crash Types	Crash Severity	Apply Range	Rural Signalized Intersection	
			Widening median on the major road	Widening median on the minor road
Single	KABCO	0-40	$e^{(0.0129*\text{MedMajor})}$	–
All Types	KABC	0-10	–	$e^{(-0.0117*\text{MedMinor})}$
All Types	KAB	0-10	–	$e^{(-0.0114*\text{MedMinor})}$

6.5 Changes of Intersection Angle Level

6.5.1 Crash Modification Factors

After we prepared the data, we conducted cross-sectional studies to see the skew angle has significant influence on rural signalized intersections. We checked the significance for many crash types including KABCO, KABC, KAB, single vehicle, multiple vehicle, day time, night time, rear-end, and angle+left turn. The impact of skew angle was examined for each of the crash types. We discovered that there is a significant different for intersections with skew angle 45 degree or less and the intersections which skew angle is greater than 45 degree. In this case, we modeled the SPFs separately into 2 groups. All skew angles in the first subsample are less than 45 degree. On the other hand, in the second subsamples, all the skew angles are greater or equal than 45.

Accordingly, for intersections with 45 degree or less, we use 0 as the base to serve as a reference to compare higher skew angles. In this category, the results are shown in Table 6-12. We found the single vehicle crashes decreased after decreasing of the skew angle. In fact, other crash category such as total crash has no significant change after changing skew angle. The CMFs were estimated based on the GLM in Table 6-13.

Table 6-12: CMF for Decreasing Skew Angle Based on 0 Degree Base

Treatment	Setting (Road type)	Traffic Volume on the Major Road (AADT)	Traffic Volume on the Minor Road (AADT)	Skew Angle (Degree)	Crash Type (Severity)	CMF	S.E.
Change Skew Angle	Rural	2,725 - 29,500	170 - 14,500	10 Degree to 0 Degree	Single (KABCO)	0.88*	0.06
				20 Degree to 0 Degree	Single (KABCO)	0.78*	0.12
				30 Degree to 0 Degree	Single (KABCO)	0.69*	0.17
				40 Degree to 0 Degree	Single (KABCO)	0.61*	0.23

Note: all CMF values are significant at a 90% confidence interval

Table 6-13: NB Model for Single Vehicle Crashes

	Single (KABCO) crashes		
Parameter	Coeffi-cient	SE	p-value
Constant	-6.8004	1.6688	<0.0001
Ln(Major AADT)	0.5293	0.1900	0.005
Skew Angle	0.3893	0.1278	0.086
Dispersion	0.819		
Deviance	200.06		
AIC	800.37		

6.6 Installation of Retro-reflective Border Back Plates

6.6.1 Crash Modification Factors

The CMFs are shown in Table 6-14. In this table, CMFs for two crash types are examined. Due to the limitation of treated sites, both CMFs for these two crash types are not significant at a 90 percent level. Based on the predicted value (mean value) of CMF, the CMF for total crashes at all time is very close to 1 but not significant at 90 percent. On the other hand, the night time CMF is slightly lower than 1 with 12 percent reduction however not significant at 90 percent as well. The CMFs were estimated using the cross-sectional method based on the developed SPFs in Table 6-15 and Table 6-16.

Table 6-14: CMF for Install Retroreflective Backplates to Signals

Treatment	Setting (Road type)	Crash Type (Severity)	CMF	S.E.
Install Retroreflective Backplates to Signals	Urban	All types (KABCO)	0.717*	0.095
		All types (KABC)	0.739*	0.104
		All types (Rear-End)	0.779*	0.116
		All types (Day Time)	0.711*	0.103
		All types (Night Time)	0.672*	0.114

*: Significant at a 90% confidence level

Table 6-15: SPFs for KABCO, KABC, and Rear End Crashes

	All Types (KABCO) crashes			All Types (KABC) crashes			Rear-End (KABCO) crashes		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-5.0398	1.2909	<0.0001	-4.129	1.3813	<0.0001	-7.4491	1.4872	<0.0001
Ln(Major AADT)	0.5959	0.1213	<0.0001	0.4529	0.1286	<0.0001	0.7154	0.1386	<0.0001
Ln(Minor AADT)	0.2475	0.0701	0.0004	0.1735	0.0728	0.0171	0.3002	0.0789	0.0001
Retro-Back Plate	-0.3332	0.1323	0.0118	-0.3031	0.1407	0.0312	-0.2496	0.1487	0.0934
Dispersion	0.2345			0.0001			0.2705		
Deviance	153.81			136.89			158.39		
AIC	862.19			611.42			746.94		

Table 6-16: SPFs for Day- and Nighttime Crashes

	Day-Time (KABCO) crashes			Night-Time (KABCO) crashes		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-5.0469	1.413	0.0004	-5.4644	1.6572	0.001
Ln(Major AADT)	0.5605	0.1326	<0.0001	0.5061	0.1542	0.001
Ln(Minor AADT)	0.2492	0.0765	0.0011	0.244	0.8726	0.0052
Retro-Back Plate	-0.3415	0.1447	0.0183	-0.3973	0.1688	0.0186
Dispersion	0.2701			0.2747		
Deviance	143			140.48		
AIC	801.02			609.53		

6.7 Installation of Red Light Running Warning Sign with Citation Amount Specified at Upstream of the Intersection

6.7.1 Safety Performance Functions

The SPFs are shown in Table 6-17. In this table, three combination of crash severities are examined. According to the NB models, we can tell from the negative coefficient of installing RLR sign, that installing red light running warning sign with citation amount specified upstream of the intersection would decrease crashes at intersections with AADT exceeding 50,000.

Table 6-17: Developed SPFs

Observations: 92	*Dependent variable:*		
	KABCO (1)	KABC (2)	KAB (3)
Ln (Entering AADT)	1.076***	0.844***	0.761***
	(0.167)	(0.167)	(0.173)
High Volume * Sign	-0.298***	-0.245**	-0.230**
	(0.156)	(0.156)	(0.158)
Low Volume * Sign	0.208*	0.226	0.221*
	(0.162)	(0.162)	(0.167)
Constant	-8.092***	-6.227***	-6.103***
	(1.826)	(1.831)	(1.899)
Log Likelihood	-402.092	-344.350	-275.150
Overdispersion	3.219*** (0.510)	3.509*** (0.621)	4.232*** (0.935)
AIC	812.183	696.700	558.300
Note:			*p<0.1;* ***p<0.05;*** p<0.01

6.7.2 Crash Modification Factors

In addition, the CMFs are exhibited in Table 6-18. These safety improvements are significant at 90 percent level for KABCO and KABC. On the other hand, this treatment has opposite effect towards intersections with low AADT, however, not significant at 90 percent level. Accordingly, since the crash increment is not significant for the intersection with low AADT, we conclude that installing red light running warning sign with citation amount specified at upstream of the intersection has positive effect to limit traffic crashes. Specifically, it is also recommended to implement this treatment at the intersections with higher traffic volume as suggested by the results.

Table 6-18: Developed CMFs for Adding RLR Citation Sign

Treatment	Setting (Road type)	Traffic Volume Entering Intersection (AADT)	Crash Type (Severity)	CMF	S.E.
Red Light Running Warning Sign with Citation Amount Specified	Rural +Urban	AADT > 50,000	All types (KABCO)	0.742*	0.116
			All types (KABC)	0.783*	0.122
			All types (KAB)	0.795	0.126
		AADT < 50,000	All types (KABCO)	1.231	0.2
			All types (KABC)	-	-
			All types (KAB)	1.247	0.209

*: significant at a 90% confidence interval

6.8 Converting Traditional and Hybrid Toll Plazas to All Electronic Toll Collection

6.8.1 Safety Performance Functions

The NB regression models were developed for different crash types and injury levels. A set of SPFs were developed for the hybrid mainline toll plaza (HMTP) as shown in Table 6-19. The SPF models included many crash related factors. However, only log (AADT), speed limit, and the location (Upstream and Downstream of the toll plaza) came out to be significant in the final models of the All (KABCO), All (KABC), and lane change related crashes (LCRC). And only log (AADT) was significant in the final models of the PDO and rear end crashes.

Table 6-19: Estimated Parameters of GLMs for Different Crash Types and Severity Levels

	Coefficient				Dispersion (k)	AIC
	Intercept	Ln (AADT)	Speed Limit	Location*		
Crash Type (Severity)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)		
All (KABCO)	-11.8525 (<0.0001)	1.1181 (<0.0001)	0.0574 (0.0215)	-	0.3128	208.67
All (KABC)	-14.8636 (<0.0001)	1.2362 (<0.0001)	0.0629 (0.0269)	-	0.2207	180.483
All (O)	-9.1515 (<0.0001)	1.1708 (<0.0001)	-	-	0.3273	172.799
LCRC* (KABCO)	-12.8711 (<0.0001)	1.1993 (<0.0001)	-	-0.8555 (0.0010)	0.2028	100.618
Rear End (KABCO)	-8.8567 (<0.0001)	1.0746 (<0.0001)	-	-	0.4450	165.867

Location*: dummy variable (i.e., upstream of toll plaza=1 and downstream of toll plaza=0)
LCRC*: lane change related crashes (i.e., sideswipe and angle crashes)

In order to reflect the changes of crashes based on time trend, the yearly factors are calculated and used in the analysis. The yearly factor, suggested by Hauer, 1997 and Gross et al., 2010, is calculated as the sum of the observed crashes divided by the sum of the crashes predicted by the SPF in that year. The calculated yearly factors are illustrated in Table 6-20.

Table 6-20: Yearly Factors

Year	2003	2004	2005	2006	2007	2008
Yearly factor	1.01	0.98	0.97	1.03	0.96	0.92
Year	2009	2010	2011	2012	2013	2014
Yearly factor	0.94	0.98	1.05	0.95	0.89	0.93

6.8.2 Crash Modification Factors

The before-after with EB technique was used to evaluate the safety effects of all electronic toll collection (AETC) system. Table 6-21 presents the CMFs for the converting traditional and hybrid mainline toll plazas to all electronic toll collection treatment. The results show that both converting traditional mainline toll plaza (TMTP) and HMTP to AETC are safety effective in reducing All (KABCO), All (KABC), All (O), LCRC (KABCO), and Rear End (KABCO) crashes. In particular, conversion of TMTP to AETC is more safety effective than conversion of HMTP to AETC.

Table 6-21: Developed CMFs

Crash Type (Severity)	TMTP to AETC		HMTP to AETC	
	CMF	S.E	CMF	S.E
All (KABCO)	0.24	0.06	0.76	0.08
All (KABC)	0.25	0.08	0.72	0.06
All (O)	0.32	0.07	0.80	0.10
LCRC (KABCO)	0.26	0.04	0.78	0.07
Rear End (KABCO)	0.20	0.09	0.78	0.09

Note: all CMF values are statistically significant at a 95% confidence level

6.9 Converting HOV Lanes to HOT Lanes

6.9.1 Safety Performance Functions

In order to estimate CMFs using EB method, the simple SPFs were developed as shown in Table 6-22. The research team also tried to develop full SPFs but it was not significant.

Table 6-22: Estimated Parameters of GLMs for Different Crash Types and Severity Levels

Crash Type (Severity)	Intercept Estimate (P-Value)	Ln (AADT) Estimate (P-Value)	Dispersion (k)
All (KABC)	-2.0639 (0.0325)	0.6532 (0.0526)	0.4495
LCRC* (KABCO)	-1.3652 (0.0002)	0.6325 (<0.0001)	0.5656
Rear End (KABCO)	-5.4648 (0.0623)	0.8312 (0.0060)	0.9596
All others (KABCO)	-1.7418 (0.0231)	0.7360 (0.0037)	0.4784

LCRC*: lane change related crashes (i.e., sideswipe and angle crashes)

6.9.2 Crash Modification Factors

Two NB regression models were developed to estimate CMFs using the cross-sectional method as shown in Table 6-23. In general, all parameters are statistically significant at a 95% confidence level.

The CMFs were also estimated using CG and EB methods. Both methods consistently show that the safety effects of the treatment would significantly affect the safety performance of HOT lanes only. This may be attributable to the fact that the HOT lanes became a highway within a highway, and traffic in these lanes will involve less congestion and more smooth flow as well as less lane changes. Table 6-24 shows the CMFs for converting HOV lanes to HOT lanes treatment.

Table 6-23: Estimated Parameters of NB Models

	Intercept	Ln (AADT)	HOT Lanes	
Crash Type (Severity)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Dispersion (k)
All (KABCO)	-14.3891 (<0.0001)	1.4644 (<0.0001)	-0.2212 (<0.0001)	0.4128
All (O)	-13.3883 (0.0011)	1.2506 (0.0002)	-0.4695 (0.0008)	0.5656

Table 6-24: Developed CMFs

Crash Type (Severity)	CS method		CG method		EB method	
	CMF	S.E	CMF	S.E	CMF	S.E
All (KABCO)	0.80**	0.10	-	-	-	-
All (KABC)	-	-	0.70**	0.12	0.72**	0.12
All (O)	0.63**	0.11	-	-	-	-
LCRC (KABCO)	-	-	0.65**	0.12	0.61**	0.10
Rear End (KABCO)	-	-	0.57**	0.09	0.62**	0.07
All Others (KABCO)	-	-	0.71*	0.16	0.77*	0.13

**: significant at 95% confidence level, *: significant at 90% confidence level

CHAPTER 7. IMPROVEMENT OF TREATMENTS IN PHASE I

7.1 Adding Shoulder Rumble Strips on Rural Two-lane Roadways

7.1.1 Introduction

In the Phase I, the RCI data from 2007 to 2009 for the whole state were used for finding shoulder rumble strips on rural two-lane roadways treated sites and comparison group data. In order to find more treated sites and improve the estimated CMFs in Phase I, the RCI data from 2004 to 2011 were obtained. Moreover, Florida-specific full SPFs were developed and used for the re-evaluation whereas simple SPFs were used previously. Since this collected data contained two additional new treatments (widening shoulder width, shoulder rumble strips + widening shoulder width), the analysis results were discussed in Chapter 5. Table 7-1 provides the comparison between CMFs from Phase I and Phase II.

Table 7-1: Re-evaluated CMFs for Adding Rumble Strips on Rural Two-lane Roadways and Comparison with Previous CMFs

	Phase II		Phase I	
Crash Type (Severity)	CMF	S.E	CMF	S.E
All (KABCO)	**0.83****	0.07	0.70**	0.11
All (KABC)	**0.84***	0.08	0.78*	0.12
SVROR (KABCO)	**0.75***	0.14	0.56**	0.18
SVROR (KABC)	**0.80**	0.16	0.68	0.25

**: significant at a 95% confidence level, *: significant at a 90% confidence level
Note: Values in bold denote the suggested CMFs

7.2 Increasing Lane Width on Rural Roadways

7.2.1 Introduction

In the Phase I, the CMFs for increasing lane width on rural roadways showed negative safety effects (i.e., CMF >1) due to inappropriate classification of roadway types. A set of rural freeway segments were excluded from the dataset. Also, more years of crash data were considered additionally. Moreover, for rural multilane roadways, the dataset has been divided into two categories (i.e., dividied and undivided mulilane roadways).

For the analysis for increasing lane width on rural two-lane roadways, in order to consider and investigate multiple treatments impact (i.e., interaction effects with new treatments), the analysis results were presented in Chapter 5. It should be noted that the opposite effects were found from Phase II.

7.2.2 Safety Performance Function

Four Florida-specific full SPFs were developed using the NB model for rural divided and undivided multilane roadways as presented in Table 7-2. The full SPFs were developed for All crashes and for the following two severity levels: (1) KABCO and (2) KABC. All variables are significant at a 90% confidence level except one case (i.e. combination of AADT and lane width for undivided roadways for KABCO), respectively.

Table 7-2: Developed Full SPFs for Rural Multilane Roadways

(a) Divided Roadway

	KABCO			KABC		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-9.7335	1.7079	<.0001	-8.4473	1.7539	<.0001
Ln(AADT)	1.6838	0.3859	<.0001	1.5107	0.3727	<.0001
Length	0.3090	0.1112	0.0055	0.3916	0.1107	0.0004
Ln(AADT)×Lane width	-0.0391	0.0232	0.0920	-0.0437	0.0218	0.0445
Shoulder width	-0.1000	0.0453	0.0275	-0.0784	0.0454	0.0841
Dispersion	1.5404			1.3240		
Log likelihood	-443.7208			-346.8109		
AIC	899.4417			705.6217		

(b) Undivided Roadway

	KABCO			KABC		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	-9.0590	1.6120	<.0001	-7.0879	1.5390	<.0001
Ln(AADT)	1.2312	0.2283	<.0001	1.0084	0.2260	<.0001
Length	0.8148	0.3549	0.0271	0.6817	0.3044	0.0251
Ln(AADT)×Lane width	-0.0169	0.0117	0.1493	-0.0219	0.0125	0.0809
Dispersion	2.3317			1.8922		
Log likelihood	-468.7450			-357.1455		
AIC	947.4899			724.2910		

7.2.3 Crash Modification Factors

The CMFs from Phase I and the CMFs in the HSM are presented in Table 7-3. Also the CMFs estimated using the cross-sectional method from Phase II are presented in Table 7-4. In general, although the CMFs from Phase I showed that the safety effects increase as lane width decreases, the opposite effects were found from Phase II. This result is consistent with the CMFs in the HSM.

It should be noted that the CMFs developed from Phase II interact with AADT. Two ranges of AADT level (1000 to 5000 veh/day and 5001 to 36000 veh/day) were categorized and most frequent AADT levels were selected from each group to represent low and high traffic volumes. In Table 7-4, the CMFs were estimated for the selected two AADT levels (3000 and 15000 veh/day) to explore the variation of CMFs based on AADT changes. The results show that the CMFs for changes of lane width are more safety effective as AADT level increases. The summary of developed CMFunctions to estimate CMF in the cross-sectional method is presented in Table 7-5.

Table 7-3: Developed CMFs from Phase I and the CMFs in the HSM

		Florida-specific		HSM
Setting (Road type)	Lane Width	CMF	SE	CMF
Rural (Undivided Multi-lane)	9-ft or less 10-ft 11-ft 12-ft or more	-	-	1.04~1.38 1.02~1.23 1.01~1.04 1.00
Rural (Divided Multi-lane)	9-ft or less 10-ft 11-ft 12-ft or more	0.44 0.58 0.76 1.00	0.16 0.13 0.07 -	1.03~1.25 1.01~1.15 1.01~1.03 1.00

Table 7-4: Developed CMFs from Phase II

Changes of lane width	Divided				Undivided			
	KABCO		KABC		KABCO		KABC	
	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
AADT= 3,000								
12 to 10 ft	1.87**	0.03	2.01**	0.02	1.31**	0.05	1.42**	0.05
12 to 10.5 ft	1.60**	0.03	1.69**	0.02	1.23**	0.06	1.30**	0.05
12 to 11 ft	1.37**	0.02	1.42**	0.02	1.14**	0.06	1.19**	0.05
12 to 11.5 ft	1.17**	0.02	1.19**	0.02	1.07	0.06	1.09*	0.05
Base: 12 ft	1.00	-	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	0.86**	0.02	0.84**	0.02	0.93	0.06	0.92*	0.05
12 to 13 ft	0.73**	0.02	0.70**	0.01	0.87**	0.06	0.84**	0.05
12 to 13.5 ft	0.63**	0.02	0.59**	0.01	0.82**	0.06	0.77**	0.05
12 to 14 ft	0.53**	0.02	0.50**	0.01	0.76**	0.06	0.70**	0.04
AADT= 15,000								
12 to 10 ft	2.12**	0.02	2.32**	0.02	1.38**	0.05	1.52**	0.04
12 to 10.5 ft	1.76**	0.02	1.88**	0.02	1.28**	0.05	1.37**	0.04
12 to 11 ft	1.46**	0.02	1.52**	0.02	1.18**	0.05	1.23**	0.04
12 to 11.5 ft	1.21**	0.02	1.23**	0.01	1.08	0.05	1.11**	0.04
Base: 12 ft	1.00	-	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	0.83**	0.01	0.81**	0.01	0.92	0.05	0.90**	0.04
12 to 13 ft	0.69**	0.01	0.66**	0.01	0.85**	0.05	0.81**	0.04
12 to 13.5 ft	0.57**	0.01	0.53**	0.01	0.78**	0.05	0.73**	0.04
12 to 14 ft	0.47**	0.01	0.43**	0.01	0.72**	0.05	0.66**	0.03

**: significant at a 95% confidence level, *: significant at a 90% confidence level

Table 7-5: Summary of Developed CMFunctions

	Divided		Undivided	
	KABCO	KABC	KABCO	KABC
Changes of lane width × AADT	$\exp\{-0.0391 \times \ln(AADT) \times (LW - Base_{LW})\}$	$\exp\{-0.0437 \times \ln(AADT) \times (LW - Base_{LW})\}$	$\exp\{-0.0169 \times \ln(AADT) \times (LW - Base_{LW})\}$	$\exp\{-0.0219 \times \ln(AADT) \times (LW - Base_{LW})\}$

7.3 Adding a Bike Lane on Urban Arterials

7.3.1 Introduction

Bike lanes are mostly placed in the shoulder of roadways and bicyclists are simultaneously riding next to vehicles. Therefore, there are higher chances of conflicts between bicycles and vehicles. Bike lanes can reduce the number of conflicts by separating bicyclists from vehicles with bicyclists' own designated path. Thus, bike lanes are likely to reduce bike crashes. In the previous Phase, the CMFs for adding a bike lane on urban arterials treatment were developed using the cross-sectional method. According to the HSM, observational before-after evaluation techniques are considered as higher quality approaches than the cross-sectional method due to its strength to account for the regression to the mean (RTM) threat. In order to improve the CMFs for adding a bike lane on urban arterials treatment, observational before-after with EB method was adopted.

7.3.2 Data Preparation

Using RCI and Financial Management databases, the sites with treatment (adding a bike lane) were identified. The total length of the treated urban arterials is 37.671 miles long and the total number of the treated segments is 227. Also, the reference sites that have similar roadway characteristics to the treated sites in the before period were identified using the RCI database. The reference sites were selected from the same region as the treated sites to improve comparability between the reference and treated sites. Transtat-Iview and Google Earth were used to verify and modify the RCI and financial project information data, if there were any missing values.

In addition to these traffic and roadway geometric characteristics, socio-economic parameters were collected for each site. The socio-economic and demographic parameters were collected from the U.S. Census Bureau website using PLANSAFE Census Tool (Washington et al., 2010). Moreover, this census information was aggregated for the geographic entity (Block Groups) using the same tool. There are two types of geographic entity (Block Groups and Census Tracts) in the U.S. Census and the Block Groups are smaller zone units than the Census Tracts. According to Levine et al., (1995), choosing relatively small spatial zone units can associate characteristics of the zone with crashes and avoid the biases caused by aggregation. Moreover, the zone size of urban areas is much smaller than rural areas, and therefore each zone in the urban areas has relatively small number of roadway segments. Thus, socio-economic parameters in each zone with small spatial units can be more accurately reflected on the roadway segments in urban areas.

The crash data were obtained from CARS for these treated and reference sites in before and after periods. All sites (227 roadway segments) that have been treated in the years between 2006 and 2009 were selected for analysis to ensure sufficient sample size. The crash data was extracted for each site for 3-year before (2003-2005) and 3-year after periods (2010-2012). This criterion for crash data was used consistently for the before-after analysis. Roadway characteristics of the treated site were matched with crash data by roadway ID and segment mile point for each site.

The intersection- related crashes were removed. Table 7-6 presents the descriptive statistics of the variables for the treated sites.

Table 7-6: Descriptive Statistics of Treated Segments

Variable Name	Definition	Mean	S.D.	Min.	Max.	Total
Crash frequency in before period						
All (KABCO)	Number of crashes for all crash types and all severity levels	5.9824	7.3911	0	35	1358
All (KABC)	Number of crashes for all crash types and KABC severity levels	3.6608	4.6710	0	24	831
Bike (KABCO)	Number of bike crashes for all severity levels	0.1410	0.4773	0	3	32
Bike (KABC)	Number of bike crashes for KABC severity levels	0.0264	0.1608	0	1	6
Crash frequency in after period						
All (KABCO)	Number of crashes for all crash types and all severity levels	4.7533	6.1795	0	30	1079
All (KABC)	Number of crashes for all crash types and KABC severity levels	2.8678	4.2354	0	24	651
Bike (KABCO)	Number of bike crashes for all severity levels	0.0529	0.2772	0	2	12
Bike (KABC)	Number of bike crashes for KABC severity levels	0.0088	0.0937	0	1	2
Variable Name	Definition	Mean	S.D.	Min.	Max.	
Variables related to traffic and roadway geometric characteristics						
AADT	Annual Average Daily Traffic (veh/day)	35,262	17,880	10,845	76,500	
No_Lanes	Number of lanes (2 lanes = 49 sites, 4 lanes = 97 sites, 6 lanes = 50 sites, 8 lanes = 31 sites)					
AADT_Lanes	AADT per lane (veh/day/lane)	7,708	1,988	3,200	12,750	
Length	Segment length (mile)	0.1565	0.1777	0.11	0.97	
Surf_width	Total surface width of roadway (ft)	55.63	21.5	22	96	
Bike_width	Width of paved bike lane (ft)	4.9339	1.9048	3	10	
Med_width	Median width (ft)	26.427	14.215	0	46	
Lane_width	Width of vehicle travel lane (ft)	11.805	0.472	10.667	13.333	
Med_type	Type of median (1 = with barrier, 0 = no barrier)	1 = 25.55%, 0 = 74.45%				
Sidewalk	Sidewalk for pedestrian (1 = yes, 0 = no)	1 = 39.65%, 0 = 60.35%				
Demographic and socio-economic variables						
Log_Pop_Den	Log of population density (per square mile)	7.3547	0.7539	4.5074	9.1965	
Log_Med_Inc	Log of median household income of each zone (US Dollars)	10.8222	0.4297	9.7193	11.86	
P_High_edu	Proportion of people with education level less than high school	0.1223	0.1025	0	0.4436	
P_Pub_Comm	Proportion of commuters by public transport in total commuters	0.0048	0.013	0	0.0867	
P_Bike_Comm	Proportion in total commuters of commuters by bicycle in total commuters	0.0067	0.0151	0	0.0879	
P_Walk_Comm	Proportion of commuters by walk in total commuters	0.0074	0.02	0	0.1797	
Avg_Const_Yr	Average construction year of structures (1 = average construction year of structures is before 1987, 0 = average construction year of structures is after 1987)	1 = 62.11%, 2 = 37.89%				

7.3.3 Safety Performance Functions

In order to adopt the before-after with EB method, four Florida-specific full SPFs were developed using the NB model for reference sites of urban arterials as presented in Table 7-7. A total of 517 roadway segments with 73.167 mile in length were identified as reference sites that have similar roadway characteristics as the treated sites in the before period. Roadway characteristics and the matched crash data were collected from the RCI and CARS databases, respectively. In reference sites, there were 1,977 KABCO and 1,239 KABC crashes for Total crashes, and 63 KABCO and 59 KABC crashes for Bike crashes. The full SPFs were developed for the following four combinations of crash type and severity level: 1) All crashes (KABCO), 2) All crashes (KABC), 3) Bike (KABCO), and 4) Bike (KABC). All variables are significant at a 90% confidence level, respectively. In general, the results of four full SPFs show that crash frequency is higher for the roadway segments with higher AADT and longer length. It is worth noting that crash frequency decreases as median household income increases. This may be because income level is correlated with the other socio-economic factors such as education level and employment rate, and these factors can contribute to the higher crash risk (Huang et al., 2010; Abdel-Aty et al., 2013).

Table 7-7: Full SPFs

	Coefficient				Dispersion (k)	Goodness of Fit	
	Intercept	Ln (AADT)	Segment Length	Ln (Median Household Income)		Deviance	AIC
Crash Type (Severity)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)	Estimate (P-Value)			

All (KABCO)	-3.3762 (0.0851)	1.0823 (<0.0001)	2.9507 (<0.0001)	-0.5513 (<0.0001)	1.6224	587.3420	3293.5609
All (KABC)	-3.7374 (0.0546)	1.0374 (<0.0001)	3.1437 (<0.0001)	-0.5350 (<0.0001)	1.5218	567.5066	2744.9946
Bike (KABCO)	-8.7589 (0.0210)	1.4849 (<0.0001)	2.7948 (<0.0001)	-0.7553 (0.0027)	1.6357	291.5820	705.3721
Bike (KABC)	-7.6940 (0.0456)	1.1417 (<0.0001)	2.7827 (<0.0001)	-0.8555 (0.0010)	1.6834	281.7257	680.2444

7.3.4 Crash Modification Factors

The CMFs estimated using the observational before-after with EB (for Phase II) and cross-sectional methods (from Phase I) are presented in Table 7-8. In general, both cross-sectional and before-after with EB methods show that the safety effects of adding a bike lane are positive (i.e., CMF < 1). Also, there was an 8% difference in the CMFs between the cross-sectional and before-after methods. The suggested CMF between the before-after with EB and cross-sectional studies was selected based on lower standard errors. It is worth to note that the CMFs estimated using EB method show lower standard errors than CMFs from cross-sectional method. However, the CMF for Bike (KABC) estimated using the before-after with EB method was not significant due to lower number of bike injury crashes. Therefore, the CMF using cross-sectional method was selected as the suggested CMF for Bike (KABC). It is worth to note that the CMFs for Bike crashes are notably lower than the CMFs for All crashes. These results imply that adding a bike lane is more effective in reducing Bike crashes.

Table 7-8: Re-evaluation and Previous CMFs

Calculation Method (Phase)	Crash Modification Factor (Standard Error)

	All crashes (KABCO)	All crashes (KABC)	Bike (KABCO)	Bike (KABC)
Before-After with EB (Phase II)	**0.83 (0.03)**	**0.80 (0.04)**	**0.44 (0.08)**	-
Cross-sectional (Phase I)	0.68 (0.08)	0.73 (0.09)	0.42 (0.10)	**0.40 (0.090)**

Note: All CMF values are significant at a 95% confidence level
Note: Values in bold denote the suggested CMFs

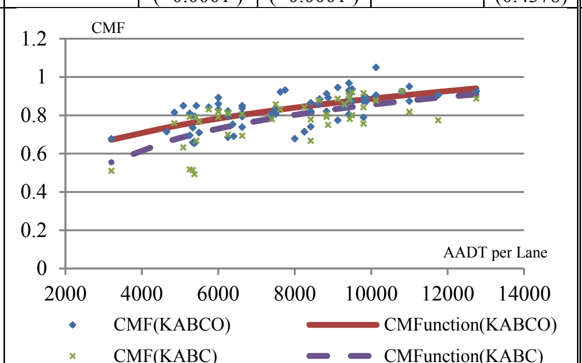
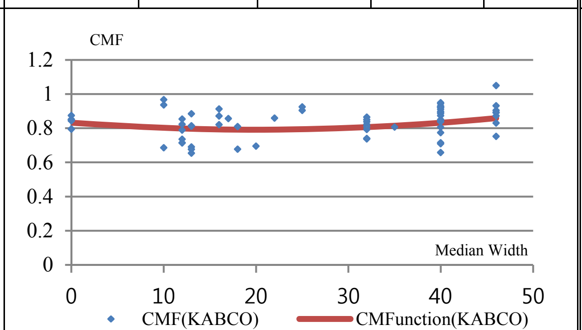
7.3.5 Crash Modification Functions

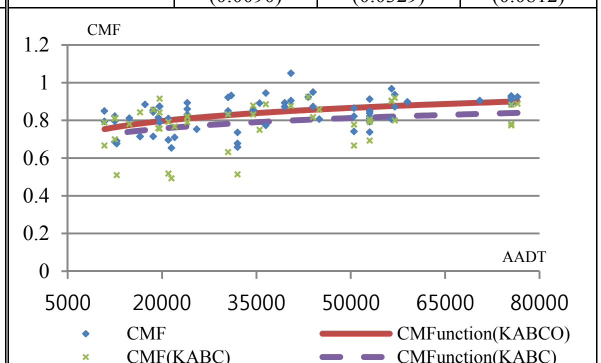
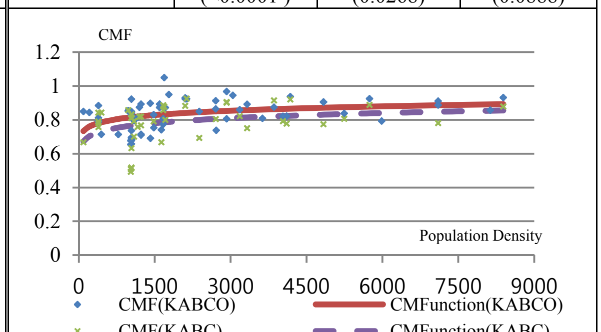
In addition to the estimation of CMFs for the adding a bike lane on urban arterials treatment, the research team also developed simple and full CMFunctions using nonlinear and multiple linear regression models. The simple CMFunctions for the adding a bike lane on urban arterials treatment were developed in order to observe the variation of CMFs with different roadway characteristics. In this study, the simple CMFunction is defined as the function of any single explanatory variable, not only AADT. The effectiveness of adding a bike lane in reducing crashes by severity level was assessed for each treated site. Figure 7-1 presents the simple CMFunctions with five different roadway characteristics for two severity levels. Due to low frequency of Bike crashes, the CMFuntions were developed for All crashes only. Also, due to poor model fit, the CMFunctions for KABC crashes were not shown for median width and bike lane width in Figure 7-1. Since the simple CMFunction need to be fitted with one continuous variable, five different continuous roadway characteristics were used to estimate each CMFunction: 1) log of AADT per lane, 2) log of AADT, 3) log of population density, 4) median width and 5) bike lane width. Based on previous study by Elvik (2011), five linear and non-linear functions - Linear, Inverse, Quadratic, Power, and Exponential - were compared and the best fitted function was identified based on the R-squared value. It was found that Inverse ($y = a + b_1/x$), Quadratic ($y = a + b_1 \cdot x + b_2 \cdot x^2$), and Exponential ($y = a \cdot \exp(b_1 \cdot x)$) non-linear regression models were the best fitted functions for different roadway characteristics.

In general, the relationship between CMFs and roadway characteristics shows that the safety effects of adding a bike lane are higher for All crashes (KABC) than All crashes (KABCO). It is worth to mention that based on the relationship between CMFs and AADT per lane, the CMFs for All crashes (KABC) are notably higher than the CMFs for All crashes (KABCO) when AADT per lane is lower than 9000 veh/day whereas the CMFs for All crashes (KABC) are similar to the CMFs for All crashes (KABCO) when AADT per lane is 9000 veh/day or above. This indicates that adding a bike lane can be more effective to reduce injury crashes (KABC) for roadway segments with lower AADT.

Similar to the relationship between CMFs and AADT per lane, the result of the simple CMFunction for population density shows that the CMF increases as population density increases. Since the spatial units with higher population density have more frequent interaction among vehicles, bicyclists and pedestrians in unit area, crash risk is likely to be higher in those spatial units (Huang et al., 2010). It was also found that population is associated with traffic crashes (De Guevara et al., 2004; Huang et al., 2010) and bicycle crashes (Clifton and Kreamer-Fults, 2007; Siddiqui et al., 2012). Especially, in urban areas, due to frequent trips and various type of traffic patterns (school bus, commuting vehicles, frequent work zone, crossing pedestrians, bicyclists, motor bikes, public transportation, old drivers, etc.), there might be more chances to have conflicts and interaction between same or different type of road users. Therefore, population density can be used to reflect the variation in effects of safety treatment among different urban arterials. The result indicates that installation of bike lanes have higher safety impact on urban areas with lower population density. However, due to relatively lower R-squared value, it is recommended to use the simple CMFunctions to check general relationship between the CMFs and population density.

Moreover, it is worth to note that the simple CMFunctions for different median width and bike lane width show non-linear relationship. The results show that the CMF decreases as the bike lane width increases until 8 ft width and it increases as the lane width exceeds 8 ft. This may be because drivers tend to regard a bike lane as a normal vehicle lane or parking area when the bike lane width is similar to the width of vehicle travel lane and adequate marking or signs are not correctly used (Toole, 2010). Also, drivers may be less cautious when they perceive that there are enough spaces in the bike lane for bicycles and they are unlikely to have conflicts with bicyclists. Similarly, bicyclists may not be aware of vehicles when they are using a wide bike lane. In particular, a bike lane has higher safety effects on the urban roadways with 4 ft ~ 8 ft width. Simple CMFunctions for different median widths, the variation of CMFs is relatively small and it shows linear relationship when undivided segments are omitted in the analysis. Usually, undivided roadways have a higher likelihood of crash occurrence than divided roadways. The R-squared values of each non-linear regression model except two cases (CMFucntions with AADT per lane for KABCO and KABC) are relatively low due to insufficient sample size of segments with different roadway characteristics. Therefore, it is recommended that the simple CMFunctions be used to identify general relationships between the CMFs and the roadway characteristics, if the size of sample is not sufficient and the R-squared value of the estimated model is very low.

Crash Type (Severity)	Function	A (P-value)	B_1 (P-value)	B_2 (P-value)	r^2 (Adj r^2)
	Log of AADT per Lane				
All crashes (KABCO)	Exponential	0.0948 (0.0044)	0.2427 (<0.0001)	-	0.3965 (0.3872)
All crashes (KABC)	Inverse	2.9821 (<0.0001)	-19.5920 (<0.0001)	-	0.4506 (0.4378)
Graph					
	Median Width				
All crashes (KABCO)	Quadratic	0.8316 (<0.0001)	-0.0040 (0.1755)	0.0001 (0.0523)	0.1321 (0.1050)
All crashes (KABC)	-	-	-	-	-
Graph					
	Bike Lane Width				

Crash Type (Severity)	Function	A (P-value)	B_1 (P-value)	r^2 (Adj r^2)
	Log of AADT			
All crashes (KABCO)	Exponential	0.3233 (<0.0001)	0.0911 (<0.0001)	0.2392 (0.2275)
All crashes (KABC)	Exponential	0.3513 (0.0090)	0.0775 (0.0329)	0.1020 (0.0812)
Graph				
	Log of Population Density			
All crashes (KABCO)	Exponential	0.6036 (<0.0001)	0.0433 (0.0027)	0.1286 (0.1152)
All crashes (KABC)	Exponential	0.5298 (<0.0001)	0.0530 (0.0268)	0.1095 (0.0888)
Graph				

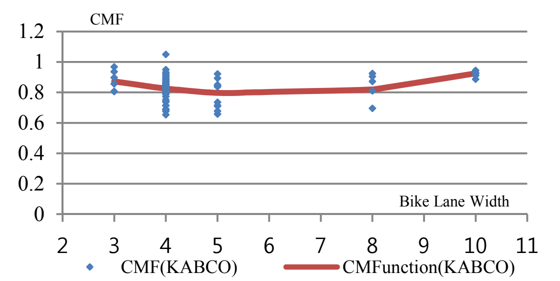
All crashes (KABCO)	Quadratic	1.1250 (<0.0001)	-0.1120 (0.0097)	0.0092 (0.0051)	0.1491 (0.1225)
Graph					

Figure 7-1: Simple CMFunctions for Adding a Bike Lane Treatment

Since it was found that CMFs are likely to vary with roadway characteristics, the relationship between CMFs and multiple roadway characteristics was also examined. Multiple linear regression models were developed to observe the variation of CMFs with multiple roadway characteristics among treated sites. It was found that the multiple regression models with backward and stepwise selections were the best fitted full CMFunctions.

Table 7-9 presents the full CMFunctions for adding a bike lane for All crashes (KABCO). It can be seen that the CMFs increase as AADT per lane increases. Also, it was found that adding a bike lane has higher safety effects for the roadways with narrow median width. This may be because the roadways with wider median width are generally representing higher roadway classification level with higher speed limit, higher traffic volume and more number of lanes. Due to these roadway characteristics, the roadways in higher functional classification level have higher crash risk due to more conflicts and lane changes. Since the simple CMFunctions show a non-linear relationship between the CMF and bike lane width, bike lane width was categorized as a binary variable (= 1 for 4 ft to 8 ft, = 0 otherwise). The results of the full CMFunction without socio-economic parameters show that the safety effects of adding a bike lane are higher for bike lanes with 4 ft to 8 ft width. On the other hand, the full CMFunction with socio-economic parameters captured the variation of CMFs with additional two socio-economic characteristics (bike commuter rates and average construction year of structures). The average construction year of structures was calculated based on the construction year of structures variable from the U.S. Census that represent average construction year of structures in each spatial unit. Based on the median year (i.e., 1987) of all observations, the median year of structures variable was set as a binary parameter (1 = structures were constructed before 1987, 0 = structures were constructed after 1987). Therefore, adding a bike lane has higher safety effects for the roadways in the zone with structures constructed before the median year. All selected variables are significant at 85% for the full CMFunction without socio-economic parameters and significant at 90% level for the full CMFunction with socio-economic parameters.

Table 7-9: Full CMFunctions for All (KABCO) Crashes

(a) All Crashes and KABCO without Socio-economic Parameters

Selection Option: Stepwise							
Analysis Of Variance							
Source	DF	Sum of Squares	Mean Square	F Value	Pr> F	R-Square	Adjusted R-Square
Model	3	0.2148	0.0716	16.75	<0.0001	0.4437	0.4172
Error	63	0.2693	0.0043				
Corrected Total	66	0.4842					

Analysis of Maximum Likelihood Estimates				
Variable	Parameter Estimate	Standard Error	T Value	Pr>|T|
Intercept	-0.7373	0.2798	-2.64	0.0106
Log AADT per Lane	0.1740	0.0312	5.58	<0.0001
Width of Bike Lane (= 1 for 4 ft to 8 ft, = 0 otherwise)	-0.0168	0.0114	-1.48	0.1447
Median Width	0.0009	0.0005	1.70	0.0932

(b) All Crashes and KABCO with Socio-economic Parameters

Selection Option: Backward							
Analysis Of Variance							
Source	DF	Sum of Squares	Mean Square	F Value	Pr> F	R-Square	Adjusted R-Square
Model	4	0.2328	0.0582	14.35	<0.0001	0.4808	0.4473
Error	62	0.2514	0.0041				
Corrected Total	66	0.4842					

Analysis of Maximum Likelihood Estimates				
Variable	**Parameter Estimate**	**Standard Error**	**T Value**	**Pr>|T|**
Intercept	-1.1217	0.2799	-4.01	0.0002
Log AADT per Lane	0.2130	0.0312	6.82	<0.0001
Median Width	0.0014	0.0006	2.60	0.0116
Bike Commuter Rate	1.3573	0.5579	2.43	0.0179
Average Const. Year (1 = structures were constructed before 1987, 0 = structures were constructed after 1987)	-0.0160	0.0089	-1.79	0.0781

The full CMFunction for All crashes (KABC) were developed as shown in Table 7-10. However, no socio-economic parameter was significant. The result of full CMFunction shows that the CMFs are lower for bike lane with 4 ft to 8 ft width. It can be seen that the CMFs vary with number of lanes. All selected variables are significant at 90% level for the full CMFunction.

It was found that both full CMFunctions with and without socio-economic parameters for the two severity levels show better model fit than any simple CMFunctions. This indicates that the CMFs vary with multiple roadway conditions. It was also found that the full CMFunction with socio-economic parameters show better model fit than the full CMFunction without socio-economic parameters for All crashes (KABCO). Therefore, it is recommended to use the full CMFunction with socio-economic parameters for All crashes (KABCO) to estimate the safety effectiveness of adding a bike lane on urban arterials, if data is available. On the other hand, socio-economic parameters were not significant in the full CMFunction for All crashes (KABC). This implies that socio-economic parameters can improve CMFunctions only for specific crash types and severity levels. Thus, it is recommended to develop multiple regression models to predict the variation in the safety effects of treatments among the treated sites with multiple roadway characteristics. Table 7-11 presents a summary of the estimated simple and full CMFunctions for adding a bike lane for different severity levels.

Table 7-10: Full CMFunctions for All (KABC) Crashes

Selection Option: Backward							
Analysis Of Variance							
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr> F**	**R-Square**	**Adjusted R-Square**
Model	5	0.2792	0.0558	8.56	<0.0001	0.5232	0.4621
Error	39	0.2544	0.0065				
Corrected Total	44	0.5336					

Analysis of Maximum Likelihood Estimates					
Variable		**Parameter Estimate**	**Standard Error**	**T Value**	**Pr>|T|**
Intercept		-1.6928	0.4659	-3.63	0.0008
Log AADT		0.2402	0.0445	5.40	<0.0001
Number of Lanes (Base: 8 lanes)	2	0.2253	0.0417	5.40	<0.0001
	4	0.0446	0.0224	1.99	0.0534
	6	-0.0977	0.0270	-3.62	0.0008
Width of Bike Lane (= 1 for 4 ft to 8 ft, = 0 otherwise)		-0.0427	0.0189	-2.26	0.0293

Table 7-11: Summary of Developed Simple and Full CMFunctions

	Simple CMFuntions				
Crash Type (Severity)	**By AADT per Lane**	**By AADT**	**By Median Width (ft)**	**By Bike Lane Width (ft)**	**By Population Density (per Sq Mile)**
All crashes (KABCO)	$CMF = 0.0948 \times EXP(0.2427 \cdot Log(AADT\ per\ Lane))$	$CMF = 0.3233 \times EXP(0.0911 \cdot Log(AADT))$	$CMF = 0.8316 - 0.0040 \cdot Median\ Width + 0.0001 \cdot Median\ Width^2$	$CMF = 1.1250 - 0.1120 \cdot Bike\ Lane\ Width + 0.0092 \cdot Bike\ Lane\ Width^2$	$CMF = 0.6036 \times EXP(0.0433 \cdot Log(Population\ Density))$
All crashes (KABC)	$CMF = 2.9821 + \frac{-19.5920}{Log(AADT\ per\ Lane)}$	$CMF = 0.3513 \times EXP[0.0775 \cdot Log(AADT)]$	-	-	$CMF = 0.5298 \times EXP(0.0530 \cdot Log(Population\ Density))$

	Full CMFunctions		
	# of Lanes	**Without Socio-economic Parameters**	**With Socio-economic Parameters**
All crashes (KABCO)	**All**	$CMF = -0.7373 + 0.1740 \cdot Log(AADT\ per\ Lane) + 0.0009 \cdot Median\ Width - 0.0168 \cdot Width\ of\ Bike\ Lane$	$CMF = -1.1217 + 0.2130 \cdot Log(AADT\ per\ Lane) + 0.0014 \cdot Median\ Width + 1.3573 \cdot Bike\ Comm\ Rate - 0.0160 \cdot Average\ Const\ Year$
All crashes (KABC)	**2**	$CMF = -1.6928 + 0.2402 \cdot Log(AADT) + 0.2253 - 0.0427 \cdot Width\ of\ Bike\ Lane$	
	4	$CMF = -1.6928 + 0.2402 \cdot Log(AADT) + 0.0446 - 0.0427 \cdot Width\ of\ Bike\ Lane$	
	6	$CMF = -1.6928 + 0.2402 \cdot Log(AADT) - 0.0977 - 0.0427 \cdot Width\ of\ Bike\ Lane$	
	8 (base)	$CMF = -1.6928 + 0.2402 \cdot Log(AADT) - 0.0427 \cdot Width\ of\ Bike\ Lane$	

7.4 Widening Shoulder Width on Rural Multilane Roadways

7.4.1 Introduction

In order to find more sites with widening shoulder width on rural multi-lane roadways treatment and improve the CMFs in Phase I, 1) the RCI data from 2004 to 2011 were obtained and compared, 2) Florida-specific full SPFs were developed and used instead of simple SPFs, and 3) safety effects for more crash types and severity levels were investigated.

7.4.2 Data Preparation

Treated sites were identified from the financial project information and the RCI dataset. All segments that have been treated in the years between end of 2006 and beginning of 2009 were selected for analysis to ensure sufficient sample size. Crash records were collected for 2 years (2004-2005) for before period and 2 years (2010-2011) for after period from CARS. The total 241 treated roadway segments with 185.822 miles long and 1796 reference sites with 881.882 miles in length were identified, respectively. It is worth to note that in Phase I, total 75 treated sites with 102.071 miles long were used to estimate the CMFs. Distributions of each variable among these treated segments are summarized in Table 7-12.

Table 7-12: Descriptive Statistics of Treated Segments

	Crash frequency in before period				Crash frequency in after period			
Variable	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Number of All (KABCO) crashes	4.037	6.773	0	57	3.249	5.148	0	33
Number of All (KABC) crashes	2.398	3.850	0	24	1.680	2.750	0	19
Number of All (KAB) crashes	1.506	2.467	0	13	0.942	1.687	0	11
Number of ROR (KABCO) crashes	0.950	2.041	0	22	0.622	1.487	0	12
Number of ROR (KABC) crashes	0.577	1.253	0	10	0.344	0.881	0	7
Number of ROR (KAB) crashes	0.407	0.909	0	6	0.203	0.581	0	5

Variables related to traffic and roadway geometric characteristics				
Variable	Mean	S.D.	Min.	Max.
AADT (veh/day) in before period	20,548.02	13,491.79	4,200	60,500
AADT (veh/day) in after period	20,272.82	12,987.71	4,100	51,500
Length (mile)	0.771	1.000	0.1	4.634
Lane width (ft)	11.975	0.156	11	12
Median width (ft)	46.232	18.718	10	130
Maximum speed limit (mph)	59.274	9.519	40	70
Number of lanes	4 lanes = 226 sites, 6 lanes = 17 sites			
Original shoulder width	2 ~ 4 ft = 8 sites, 5 ~ 6 ft = 9 sites, 7 ~ 8 ft = 39 sites, 9 ~ 10 ft = 75 sites, 11 ~ 12 ft = 110 sites			
Actual widened width	1 ft = 50 sites, 2 ft = 32 sites, 3 ft = 35 sites, 4 ft = 15 sites, 5 ft = 20 sites, 6 ft = 69 sites, 7 ~ 8 ft = 15 sites, 9 ~ 10 ft = 5 sites			

7.4.3 Safety Performance Functions

For evaluation of widening shoulder width on rural multi-lane roadways treatment, six Florida-specific full SPFs were developed using the NB model for combinations of crash type and severity levels using 2-year before and 2-year after crash data. The SPFs were developed for reference sites of rural multilane roadways in Florida shown in Table 7-13. In general, the results of six full SPFs show that crash frequency is higher for the roadway segments with higher AADT and longer length. The results also show that the crash frequency is lower for the roadways with wider median widths and lower speed limits. In order to account for trend of crash frequency based on time changes, a binary variable (i.e., before period) was included to represent the 2-year before period. It is worth noting that the model with categorical variable for each year was assessed but it was not statistically significant. The results indicate that the crash frequency in the after period is lower than the before period for both All and ROR crashes

Table 7-13: FL-specific Full SPFs

	Estimated Coefficient (p-value)							Disper-sion	Deviance	AIC
Crash types	Constant	Ln.AADT	Length	Before period (2004~2005)	Maximum speed limit	Median width	Lane width			
All (KABCO)	-13.9082 (<0.0001)	1.3072 (<0.0001)	1.0244 (<0.0001)	0.0718 (0.1445)	-	-0.0047 (0.0011)	0.0953 (0.0535)	1.4801	3,507.5	13,191.2
All (KABC)	-14.2983 (<0.0001)	1.3374 (<0.0001)	1.0163 (<0.0001)	0.1122 (0.0344)	0.0125 (0.0029)	-0.0053 (0.0038)	-	1.3581	3,166.6	10,000.7
All (KAB)	-13.3037 (<0.0001)	1.1501 (<0.0001)	1.0093 (<0.0001)	0.1755 (0.0027)	0.0184 (<0.0001)	-0.0058 (0.0054)	-	1.1965	2,802.8	7,443.2
ROR (KABCO)	-11.8034 (<0.0001)	0.8311 (<0.0001)	0.8701 (<0.0001)	0.1459 (0.0888)	0.0299 (<0.0001)	-	-	1.5529	1,857.8	3,952.5

ROR (KABC)	-12.2116 (<0.0001)	0.7835 (<0.0001)	0.8644 (<0.0001)	0.1734 (0.0992)	0.0357 (<0.0001)	-	-	1.3286	1,431.5	2,681.4
ROR (KAB)	-11.6202 (<0.0001)	0.6718 (<0.0001)	0.8292 (<0.0001)	0.2513 (0.0428)	0.0419 (<0.0001)	-0.0079 (0.0937)	-	1.0601	1,167.6	1,988.2

7.4.4 Crash Modification Factors

Table 7-14 presents the re-estimated CMFs in Phase II and previous estimated CMFs in Phase I using the before-after with EB method. The suggested CMF between the Phase I and Phase II was selected based on lower standard errors. The results indicate that re-estimated CMFs show more reliable results than the previous CMF values. In general, the safety effects of widening shoulder width were positive for both All and ROR crashes. It is worth to note that the CMFs for ROR crashes are lower than the CMFs for All crashes. These results indicate that widening shoulder width is more effective in reducing ROR than All crashes. Moreover, it was found that safety effects are higher for more severe crashes.

Table 7-14: Re-evaluated and Previous CMFs

	Phase II		Phase I	
Crash Type (Severity)	CMF	S.E	CMF	S.E
All (KABCO)	**0.88****	0.04	0.84*	0.18
All (KABC)	**0.82****	0.05	0.68**	0.10
All (KAB)	**0.79****	0.06	-	-
ROR (KABCO)	**0.75***	0.08	0.68*	0.19
ROR (KABC)	**0.72***	0.10	0.77	0.28

ROR (KAB)	**0.69****	0.11		

**: significant at a 95% confidence level, *: significant at a 90% confidence level
Note: Values in bold denote the suggested CMFs

To identify changes of CMFs based on site characteristics, the safety effects of widening shoulder width were calculated for the treated sites with different original shoulder widths and actual widened widths as presented in Table 7-15. The results show that the safety effects are higher for roadway segments with narrow original shoulder width (i.e., 2 ~ 8 ft shoulder width) for both All and ROR crashes. The results also show that the safety effects of widening shoulder width are higher as actual widened width increases. Thus, it can be concluded that the safety effects vary based on the different original shoulder widths and actual widened widths among treated sites. It is worth to note that some CMFs are not significant at a 90% confidence level. Although the CMFs that are not significant at the 90% confidence level may not represent reliable safety effects of treatments statistically, it can be suggested to use the insignificant CMFs to check the general impact of treatments with relatively large variation.

Table 7-15: Estimated CMFs for Different Roadway Conditions

	Overall Safety Effects		Different Original Shoulder Width				Different Actual Widened Width			
			2 ~ 8 ft		9 ~ 12 ft		1 ~ 4 ft		5 ~ 10 ft	
Crash Type (Severity)	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
All (KABCO)	0.88**	0.04	0.72**	0.07	0.94	0.05	0.94	0.07	0.85**	0.05
All (KABC)	0.82**	0.05	0.73**	0.09	0.84**	0.06	0.85*	0.09	0.80**	0.06
All (KAB)	0.79**	0.06	0.69**	0.12	0.82**	0.08	0.84	0.12	0.77**	0.08
ROR (KABCO)	0.75*	0.08	0.66**	0.15	0.77**	0.09	0.77*	0.14	0.74**	0.09

ROR (KABC)	0.72*	0.10	0.62**	0.18	0.74**	0.11	0.73	0.17	0.71**	0.12
ROR (KAB)	0.69**	0.11	0.57**	0.19	0.73*	0.14	0.71	0.21	0.68**	0.13

**: significant at a 95% confidence level, *: significant at a 90% confidence level

7.4.5 Crash Modification Functions

The CMFunctions for the widening shoulder width on rural multilane roadways treatment were developed to determine the variation of CMFs with different site characteristics among treated segments. Due to low frequency of All (KAB) and ROR crashes, the CMFunctions were evaluated for All (KABCO) and All (KABC) crashes only. Log form of models were utilized to ensure that the CMF value from CMFunction cannot be negative estimate. The CMFunctions were developed using multiple linear regression and MARS models as shown in Table 7-16 and Table 7-17.

Overall, the results show that the CMFs increase as original shoulder width increases for both All (KABCO) and All (KABC) crashes. In other words, widening shoulder width has higher safety effects for the roadways with narrow shoulder width. To evaluate more reliable estimates, the variables for actual widened width and median width were transformed as binary variables. The results show that widening shoulder width has lower CMFs for the roadways with narrower median width. This may be because the safety treatments are generally more safety effective when they are implemented for the hazardous roadway conditions (e.g., narrower shoulder and median widths, higher traffic volumes in each lane, more roadside obstacles, etc.). As we found from the developed SPFs, the roadways with wide median width have less crashes and this indicates that narrower median width represents hazardous roadway condition. Therefore, it might be more safety effective to widen right shoulder width for the roadways with narrower median width than the roadways with wide median width. It should be noted that the treatment is still effective in reducing crashes in general. Also, it was found that the CMFs decrease as actual widened shoulder width increases.

In the MARS models, the estimated parameters of basis functions were statistically significant at a 90% confidence level. The basis functions are constructed by using truncated power functions based on knot values. In the MARS model for total crashes, the first basis function, BF0, is the intercept. The second basis function, BF1, is 10 – original shoulder width when original shoulder width is lower than 10, and is 0 for otherwise (where the knot value is 10). Other basis functions are constructed in a similar manner by using different knot values. It is worth to note that various interaction impacts among variables under different ranges based on knot values were found from MARS whereas no interaction impact was found in the linear regression models. Moreover, two variables (i.e., AADT and maximum speed limit) that were not captured in the regression model were found to be significant in MARS. The results also show that the MARS models generally provide better model fits than the regression models. This may be because MARS can account for both nonlinear effects and interaction impacts between variables. However, it is worth mentioning that since 1) MARS models are not easy to interpret and 2) regression models still perform similar to MARS, an application of the CMFunctions using multiple linear regression model can be recommended for practitioners.

Table 7-16: Developed CMFunctions Using Multiple Linear Regression Model

	All (KABCO)			All (KABC)		
Parameter	Estimate	SE	p-value	Estimate	SE	p-value
Constant	-0.5170	0.0486	<0.0001	-0.5394	0.0867	<0.0001
Original Shoulder Width in Before Period (ft)	0.0258	0.0041	<0.0001	0.0246	0.0072	0.0028
Actual Widened Shoulder Width Indicator (1:Sites with 1 ~ 4 ft shoulder width widened, 0: Sites with 5 ~ 10 ft shoulder width widened)	0.1648	0.0205	<0.0001	0.1729	0.0365	0.0001
Median Width Indicator (1: Sites with less than 40 ft median width, 0: Sites with 40 ft or more than 40 ft median width)	-0.0599	0.0250	0.0265	-0.0653	0.0446	0.1587
MSE	0.0024			0.0077		
R-squared	0.8826			0.7084		
Adj. R-squared	0.8649			0.6647		

Table 7-17: Developed CMFunctions Using MARS Model

(a) MARS model for All (KABCO) Crashes

Basis Function	Basis Function Information	Estimate	SE	p-value
BF0	Constant	-0.2257	0.0163	<0.0001
BF1	MAX (10 – Original shoulder width, 0)	-0.0151	0.0083	0.0874
BF2	MAX (Original shoulder width – 10, 0)	-	-	-
BF3	Actual Widened Shoulder Width Indicator (1:Sites with 1 ~ 4 ft shoulder width widened, 0: Sites with 5 ~ 10 ft shoulder width widened)	0.1726	0.0174	<0.0001
BF4	Median Width Indicator (1: Sites with less than 40 ft median width, 0: Sites with 40 ft or more than 40 ft median width)	-0.1720	0.0479	0.0021
BF5	BF2 × MAX (10.02127– Ln. AADT, 0)	-0.0371	0.0170	0.0426
BF6	BF4 × MAX (Original shoulder width – 6, 0)	0.0247	0.0101	0.0252
MSE =	0.0014			
R-squared =	0.9385			
Adj. R-squared =	0.9215			

(b) MARS model for All (KABC) Crashes

Basis Function	Basis Function Information	Estimate	SE	p-value
BF0	Constant	-0.5535	0.0502	<0.0001
BF1	MAX (Original shoulder width – 4, 0)	0.1001	0.0318	0.0055
BF2	Actual Widened Shoulder Width Indicator (1:Sites with 1 ~ 4 ft shoulder width widened, 0: Sites with 5 ~ 10 ft shoulder width widened)	0.1765	0.0324	<0.0001
BF3	MAX (Original shoulder width – 6, 0)	-0.0888	0.0390	0.0354

BF4	Median Width Indicator (1: Sites with less than 40 ft median width, 0: Sites with 40 ft or more than 40 ft median width)	-	-	-
BF5	BF4 × MAX (Maximum speed limit– 65, 0)	-0.0439	0.0149	0.0086
BF6	BF4 × MAX (10.16585 – Ln. AADT, 0)	-0.0565	0.0502	0.1027
MSE =	0.0049			
R-squared =	0.8329			
Adj. R-squared =	0.7865			

7.5 Installing Red Light Running Camera

7.5.1 Introduction

The CMF for red light running camera (RLC) was examined in Phase I report. However, there is potential lag of drivers' awareness of roadway treatments. Thus, the objectives of this extended study in Phase II study are to analyze the variations in the CMFs for adding RLCs over time and to predict the CMFs. This information would be helpful for traffic engineers to understand trends of safety performance of the treatments in the long term.

7.5.2 Crash Modification Factors

The crash data for adding RLCs were available for a longer time period (36 months) than the crash data for the signalization. Previous studies found that the CMFs for adding RLCs were higher than 1 for rear-end crashes and lower than 1 for angle crashes. However, due to a lack of samples for each crash type, this study focused on crash severity instead of crash type. The CMFs were calculated for total (KABCO) and KABC crashes for adding RLCs as shown in Table 7-18. For the total crashes, the CMF for the first 18 months was lower than the CMF for the 1st-36th month whereas the CMF for the 19th-36th month was higher than the CMF for the 1st-36th month. Also, the CMF for the first 18 months is significantly lower than the CMF for the 19th-36th month at a 95 confidence level.

Table 7-18: Estimated CMFs for Adding RLCs at Different Time Periods

Severity Type (Number of months after adding RLCs)	Method	
	Comparison Group Before-After	
	CMF (Safety Effectiveness)	S.E
Total Crashes (1-36)	**0.872** 12.80%	**0.056**
Total Crashes (1-18)	**0.695** 30.50%	**0.063**
Total Crashes (19-36)	1.089 -8.90%	**0.087**
KABC Crashes (1-36)	**0.652** 34.80%	**0.057**
KABC Crashes (1-18)	**0.518** 48.20%	**0.067**
KABC Crashes (19-36)	**0.789** 21.10%	**0.083**

7.5.3 Crash Modification Functions

In Phase I, we had estimated the effect of installing red light running camera (RLC). The impact of installing RLC in Florida is similar to previous studies from other states. In detail, we found the rear-end crashes will increase and angle crashes will decrease after RLCs were installed. In fact, this effect is considered as an improvement since angle crashes are more likely to crash at higher severity levels.

Installing red light running camera is not considering as a geometry change. It is a way to enforce traffic policy. In this case, the response of road users after this enforcement may be changed over time. According to previous studies, CMFs for changing the level of police enforcement frequency are not consistent for different places. Similarly, for our expectation, after installing RLCs at intersections, drivers may drive slower or tend to stop near dilemma zone. This is the reason why rear-end crashes is increasing. On the other hand, this behavior effectively decreases the threat of angle and left turn crashes due to less red running drivers. Although, this behavior is obvious, we suspect that road users reaction toward red light running camera is consistent over time. Therefore, we estimated the CMF for installing RLCs for the different time period as shown in Table 7-18. To better reflect the short-term variations in CMFs, CMFs are calculated using the observational before-after study with the comparison group method in 90-day moving windows. Then we applied the ARMA time series model to predict trends of CMFs over. Table 7-19 and Figure 7-2 show the CMFs for All (KABCO) crashes in each month and 90-day moving windows. The confidence interval for the CMFs in each month is much wider than the interval for the CMFs in 90-day moving windows. However, the predicted CMF after the 40th month is approximately 1. This suggests that the installation of RLCs would not have significant safety effects on reducing total crashes in the long term.

Table 7-19: Estimated Parameters in ARMA Model for All (KABCO) Crashes

CMF for 90-day moving windows					
Parameter	**Estimate**	**Standard Error**	**t Value**	**Approx Pr > |t|**	**Lag**
MU	0.90077	0.17081	5.27	<0.0001	0
AR1,1	0.85561	0.09832	8.7	<0.0001	1
					AIC=-3.99 SBC=-0.93

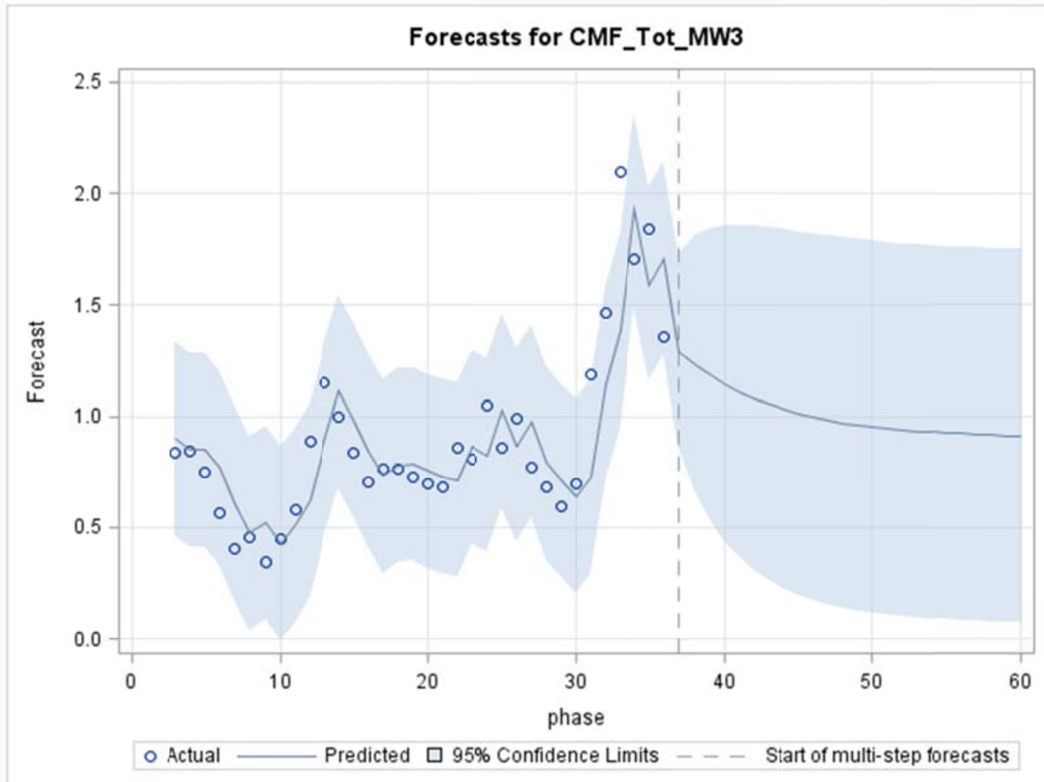


Figure 7-2: Variation of CMFs for RLCs using ARMA Model for All (KABCO) Crashes

Table 7-20 and Figure 7-3 show the changes of CMFs for All (KABC) crashes. It shows a downward trend of the predicted CMF for the first 13 months followed by an upward trend for the 13th-25th month and a downward trend after the 25th month. To take a closer look at its predicted CMF, the CMF at 40th month is lower than one. In this case, it indicates that there is higher probability that CMF will be lower than 1 for F+I crashes using moving windows however not statistically significant at 95% level.

In summary, the results of adding RLCs show that the CMFs for both All (KABCO) and All (KABC) crashes were higher during the first 18 months than the following 18 months. Thus, the CMFs for the early phase after adding RLCs did not reflect the safety performance in the later phase.

Table 7-20: Estimated Parameters in ARMA Model for All (KABC) Crashes

All (KABC) Crashes MW3					
Parameter	**Estimate**	**Standard Error**	**t Value**	**Approx Pr > |t|**	**Lag**
MU	0.64434	0.09467	6.81	<0.0001	0
AR1,1	0.73171	0.12139	6.03	<0.0001	1
AIC=-20.56 SBC=-17.51					

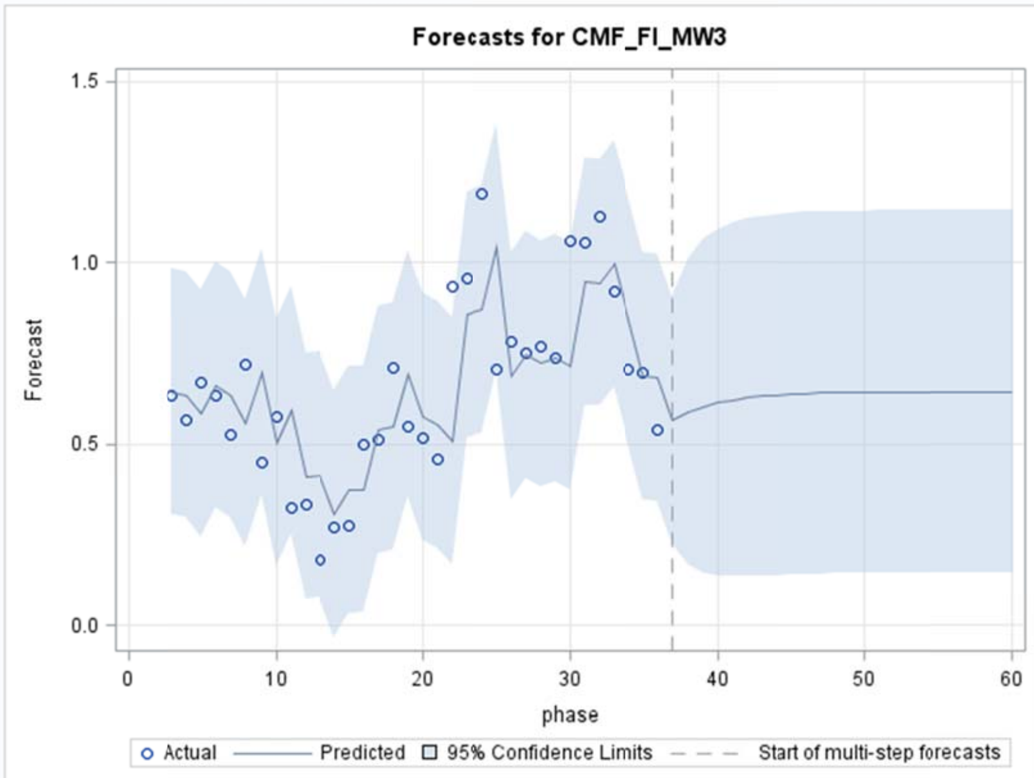


Figure 7-3: Variation of CMFs for RLCs using ARMA Model for All (KABC) Crashes

7.6 Signalization of Stop-controlled Intersection

7.6.1 Introduction

Traffic researchers and engineers have developed a quantitative measure of safety effectiveness of signalization in the form of crash modification factors. The HSM Part D provides CMFs which can be used to determine the expected number of crash reduction or increase after converting stop-controlled to signal-controlled intersections. These CMFs in HSM help engineers easily measure the safety and cost effectiveness of signalizing intersections. However, due to the differences in area type, road geometry, and traffic volume, CMFs could vary among different intersections. Therefore, it is important to understand how CMFs vary with different roadway characteristics and ensure that signalization effects on crashes are understood and CMFs calculated based on the specific characteristics of intersections, e.g., traffic volume.

7.6.2 Data Preparation

In order to estimate the safety effect of intersection signalization, 202 intersections have been identified to have been updated from a 2-way stop control intersection to a signalized intersection. We attain these intersections through the variables provided in RCI. The signalized intersections are identified along with the effective date in this road feature. We verify these locations in Google Earth to make sure the effective date is trust worthy. The numbers of 3-legged and 4-legged intersections are shown in Table 7-21. However, a good portion of minor AADT is missing. Therefore in Table 7-22, we neglect the descriptive statistics for minor AADT. Furthermore, Table 7-22, presents the descriptive statistics for comparison groups from 2003 to 2012. And the AADT used is from 2007.

Table 7-21: Proportion of 3-legged and 4-legged Intersections

	3-legged	4-legged
Number of Sites	40	162
Percentage (%)	19.8	80.2

Table 7-22: Descriptive Statistics for Comparison Group

	Mean	Standard Deviation	Minimum	Maximum
KABCO Crashes	9.86	24.4	0	313
KABC Crash	5.28	12.7	0	159
KAB Crash	3.06	7.1	0	83
Rear-End Crash	2.48	7.98	0	93
Angle+Left-turn Crash	3.69	8.99	0	85
Major AADT	9348	9342	300	56000

The descriptive statistics for each crash type are summarized in Table 7-23. Two hundred sites are found to be signalized from 2005-2010. For each site, we used 2 years before from 2003 to 2004 and 2 years after from 2011 to 2012. The crash data were retrieved from CARS database. The obtained crash records were matched with the target sites data based on its lat-long for each intersection influence area. It was found that the total crashes (KABCO) increased after signalization. On the other hand, fatal and injury crashes (KABC and KAB) were reduced after signalization. The rear-end crashes more than doubled after signalization. Angle and left turn crash decreased by 38 percent. Based on Table 7-19, we can judge that the rear-end crashes increased and the angle+left turn crashes decreased after signalization.

Table 7-23: Descriptive Statistics of Crash Records for Treated Sites (N=202)

Variable	Mean	S.D.	Min.	Max.	Crash Count
KABCO_Before	6.906	7.502	0	40	1395
KABCO_After	8.233	8.395	0	55	1663
KABC_Before	4.163	4.517	0	27	841
KABC_After	3.985	3.856	0	19	805
KAB_Before	2.386	2.755	0	16	482
KAB_After	1.847	2.045	0	12	373
Rear_End_Before	1.609	2.192	0	13	325
Rear_End_After	3.802	5.044	0	42	768
Angle_Left_Before	3.015	4.076	0	24	609
Angle_Left_After	1.876	2.296	0	13	379

7.6.3 Crash Modification Factors

In phase I, we estimated CMFs for total, rear-end, angle, and left turn crashes. We figured out that sometimes angle crashes and left turn crashes are not accurately categorized in the crash reports. To compensate for this problem, we estimated SPFs and CMFs for combined angle and left turn crashes. Due to some treatment sites have missing minor AADT. For the EB methods we used the AADT for the major road as independent variable to construct the simple SPFs. Besides, we enlarged our sample size significantly from 32 sites (phase I) to 202 sites, which is about five times more than in phase I. In addition, with more samples, we are able to estimate more crash types such as fatalities and injury crashes (F+I crashes) including KABC and KAB crashes. Other than F+I crashes, additional crashes types single vehicle, multiple vehicle, day time, and night time crashes are also estimated as well. In Table 7-24, we listed the results we provided in the phase I report. As shown in the table, HSM has missing in urban 4-legged intersection. We provide complete CMFs estimation for urban 4-legged intersections with nine crash types. Besides, the results are more promising comparing to phase I due to the sample size improvement. The detail CMF results can be shown in Table 7-25. In this table, one worth mentioning is that unlike the results in HSM and phase I, the total crashes has CMF beyond 1 for all settings. (Rural CMF for total crashes equal 1 due to rounding) In addition, the CMFs results for urban 3-legged are higher comparing to other 2 intersection types when looking at the EB results. For urban 4-legged intersections, the CMF for the rear-end crashes in the EB estimation is 2.3 which is significantly higher from what was estimated 0.7 in the phase I report. We believe this updated value is more reliable due to the increment of sample size.

Table 7-24: CMFs for Signalization Suggested in Phase I

Crash Type	Florida-Specific CMF	CMF in HSM
Rural 3-Leg & 4-Leg Intersections		
Total Crashes (S.E.)	0.98 (0.13)	**0.56*** **(0.03)**
Angle crashes (S.E.)	**0.70*** **(0.17)**	0.23* (0.02)
Rear-End Crashes (S.E.)	**1.95*** **(0.51)**	1.58* (0.20)
Left-Turn Crashes (S.E.)	**0.50*** **(0.20)**	0.40* (0.06)
Urban 3-Leg Intersections		
Total Crashes (S.E.)	0.92 (0.08)	0.95 (0.09)
Angle Crashes (S.E.)	**0.67*** **(0.11)**	0.33* (0.06)
Rear-End Crashes (S.E.)	**2.26*** **(0.48)**	2.43* (0.40)
Left-Turn Crashes (S.E.)	**0.45*** **(0.13)**	-** -**
Urban 4-Leg Intersections		
Total Crashes (S.E.)	**0.61*** **(0.06)**	-** -**
Angle crashes (S.E.)	**0.46*** **(0.08)**	-** -**
Rear-End Crashes (S.E.)	**0.71*** **(0.13)**	-** -**
Left-Turn Crashes (S.E.)	**0.66*** **(0.18)**	-** -**

*: significant at a 90% confidence level

Note: The values in **bold** denote the most reliable CMFs

Table 7-25: Re-evaluated CMFs for Signalization

Intersection Type	Crash Type	Naïve		Comparison Group		Empirical Bayes	
		CMF	Standard Error	CMF	Standard Error	CMF	Standard Error
Rural 3+4 Legs	KABCO	0.95	0.11	1.14	0.13	1.00	0.12
	KABC	0.90	0.14	0.97	0.15	0.94	0.14
	KAB	0.73*	0.14	0.82	0.16	0.75*	0.14
	Rear-End	1.78	0.52	2.84*	0.87	1.91*	0.52
	Angle+Left	0.63*	0.11	0.86	0.14	0.66*	0.11
	Single	0.94	0.31	0.88	0.29	0.94	0.31
	Multiple	0.94	0.11	1.17	0.14	1.00	0.12
	Day Time	0.95	0.13	1.21	0.16	1.00	0.14
	Night Time	1.00	0.25	0.88	0.21	1.03	0.26
Urban 3 Legs	KABCO	1.73	0.21	1.88*	0.21	1.73*	0.20
	KABC	1.23	0.19	1.38*	0.21	1.23	0.18
	KAB	0.84	0.17	1.06	0.22	0.83	0.17
	Rear-End	2.80*	0.78	3.48*	0.80	2.93*	0.66
	Angle+Left	0.98	0.18	1.18	0.21	0.98	0.17
	Single	2.59	1.18	2.84	1.14	3.12*	1.26
	Multiple	1.62*	0.20	1.85*	0.22	1.63*	0.19
	Day Time	1.55*	0.22	1.71*	0.23	1.55*	0.21
	Night Time	2.14*	0.55	2.25*	0.51	2.20*	0.50
Urban 4 Legs	KABCO	1.16	0.05	1.91*	0.09	1.17*	0.05
	KABC	0.94	0.05	1.33*	0.08	0.94	0.05
	KAB	0.79*	0.06	1.18*	0.09	0.79*	0.06
	Rear-End	2.28*	0.23	3.96*	0.37	2.30*	0.20
	Angle+Left	0.58*	0.04	0.81*	0.06	0.59*	0.04
	Single	1.21	0.18	1.72*	0.26	1.22	0.18
	Multiple	1.15*	0.05	1.91*	0.09	1.16*	0.05
	Day Time	1.16*	0.06	1.91*	0.10	1.17*	0.06
	Night Time	1.06	0.10	1.59*	0.15	1.07	0.10

*: significant at a 90% confidence level

CHAPTER 8. MULTIPLE TREATMENTS EFFECTS

8.1 Methodologies

8.1.1 Combining Methods for Multiple CMFs

To estimate the combined safety effects of multiple treatments, various methods for combining CMFs have been introduced as presented in Table 8-1. Method 1 is the most common and well known approach suggested by the HSM for combining multiple CMFs. This method was first suggested by Roy Jorgensen and Associates for estimation of overall CMF of multiple CMFs (Garber and Hoel, 2002). In Method 1, independence of treatments is assumed and the CMFs for single treatments are multiplied to estimate combined effects of multiple treatments. While Method 1 has been widely used due to the suggestion by the HSM, it should be mentioned that the assumption of independence cannot account for the potential correlations among multiple treatments and might present over-estimated results.

Method 2 and Method 3 are similar since both methods assume that expected safety effects of the less effective treatment are reduced by a factor in the equation. However, it is worth noting that the reduction factor to decrease the safety effects of the less effective treatment is fixed in Method 2 whereas the reduction factor is systematically changing based on the number of treatments in combining process in Method 3. According to the NCHRP project 17-25 (2008), these two methods were first introduced by different agencies. Although both methods can account for difference in effectiveness among multiple treatments, there is no theoretical basis for the reduction factors.

In Method 4, a specific weighting factor needs to be applied to the multiplication of CMFs for combining the safety effects of multiple treatments. This method was proposed by Turner (2011) and the weighting factor was determined based on multiple studies from New Zealand. As stated in the previous section, since the author applied this method to a specific region, which is outside the U.S., the reliability of using this method for other regions needs to be investigated.

Method 5 is also from the survey of the NCHRP 17-25 project and this method applies only the lowest CMF (i.e., the CMF for the most effective treatment) among CMFs for multiple treatments. However, this method is likely to produce under-estimated number of crashes because the potential combined effect of multiple treatments might be ignored.

Method 6 was suggested by Bahar (2010) to identify the combined effect of multiple CMFs for the same treatment. This method utilizes a weighted average of multiple CMFs and the higher weight is applied to the CMF with smaller errors. Although Method 6 was originally introduced for combining multiple CMFs for the same treatment, this method was used to combine multiple CMFs for different treatments and compared with other methods of combining CMFs (Gross and Hamidi, 2011).

Method 7 introduced by Park and Abdel-Aty (2015b) applies an adjustment factor to the combined CMFs by Method 1. The study determined this adjustment factor based on the difference between the combined CMFs and actual safety effects of multiple treatments. The study also developed CMFunctions for the variation of multiple treatments based on different roadway characteristics. Since the combined CMF and actual safety effects have variations based on different roadway conditions, the adjustment functions were developed for weighting the CMFunctions for multiple treatments. It should be noted that the adjustment function in this study was developed for specific roadway conditions and combination of treatments. Thus, an adjustment function that can be adopted more generally needs to be developed.

Lastly, Method 8 and Method 9 are from an exploratory analysis by Park et al., (2014) to obtain more reliable estimates than a simple multiplication approach. The authors suggested two adjusting approaches (i.e., averaging the best two methods and averaging the best three methods) to combine CMFs for multiple treatments. It was found that averaging the best two methods produced better estimates than using only one specific best method whereas the results from the averaging of the best three methods showed even lower performance than the best existing method. However, it is worth noting that the combinations of specific combining methods for Method 8 and Method 9 were not described. The study applied different combinations of combining CMF methods for different crash types and severity levels because the best combinations were varying for each case.

Table 8-1: Existing Methods for Combining Multiple CMFs

No.	Methods	Description	Disadvantage
1	$CMF_t = CMF_1 * CMF_2 * \cdots * CMF_n$ CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment CMF_n = CMF for the nth treatment	Assume independence of treatments	Might cause over-estimation issue
2	$CMF_{2,Reduced} = \frac{1-CMF_2}{2} + CMF_2$ $CMF_{combined} = CMF_1 * CMF_{2,Reduced}$ CMF_2 = Less effective CMF than CMF_1	Systematic reduction of safety effects of less effective treatment	No scientific background
3	$CMF_t = CMF_1 - \frac{1-CMF_2}{2} - \cdots - \frac{1-CMF_n}{n}$ CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment CMF_n = CMF for the nth treatment	Safety effects of second treatments is systematically diminished	No scientific background
4	$CMF_{combined}[TurnerMethod] = 1 - [\frac{2}{3}(1 - (CMF_1 * CMF_2))]$	Multiply weighted factor	Based on one region data (outside of US)
5	Only the lowest CMF is applied (i.e., treatment with the highest expected crash reduction)	Apply only the most effective CMF	Ignore the impact of second treatment
6	$CMF = \frac{\sum_{i=1}^{n} CMF_{unbiased,i}/S_i^2}{\sum_{i=1}^{n} 1/S_i^2}$ $\qquad S = \sqrt{\frac{1}{\sum_{i=1}^{n} 1/S_i^2}}$ CMF = combined unbiased CMF value. $CMF_{unbiased,i}$ = unbiased CMF value from study i. S_i = adjusted standard error of the unbiased CMF from study i. n = number of CMFs to be combined. S = estimate of the standard error for the combined CMF	Weighted average of multiple CMFs (Meta-Analysis)	Originally designed for combining two results from different studies for the same treatment
7	$CMF_t = U_{adj} * (CMF_1 * CMF_2 * \cdots * CMF_n)$ U_{adj}= adjustment function to adjust the combined CMF value from method 1 CMF_t = CMF for the combined treatments CMF_1 = CMF for the first treatment CMF_2 = CMF for the second treatment CMF_n = CMF for the nth treatment	Multiply adjustment function to overcome over-estimation issue	Need to develop adjustment function for specific region and roadway conditions
8	$CMF_t = (CMF_x + CMF_y)/2$ CMF_t = Adjusted CMF for the combined treatments CMF_x =combined CMF from the method x CMF_y = combined CMF from the method y	Average the best two existing combining methods	The combination of the best two methods is not specified
9	$CMF_t = (CMF_x + CMF_y + CMF_z)/3$ CMF_t = Adjusted CMF for the combined treatments CMF_x =combined CMF from the method x CMF_y = combined CMF from the method y CMF_z = combined CMF from the method z	Average the best three existing combining methods	The combination of the best three methods is not specified

8.1.2 Weighted Regression

According to Ryan (1997) and Kutner et al., (2004), a constant variance in the errors (i.e., homoskedasticity) is assumed in the ordinary least squares regression whereas the variance in the error is not constant (i.e., heteroskedasticity) in the weighted least squares (WLS). In the WLS, each weight is inversely proportional to the error variance and it reflects the information of the observation. Thus, an observation with small error variance has a large weight since it contains relatively more information than an observation with large error variance (i.e., small weight). As stated by Carroll and Ruppert (1988), the biggest disadvantage of WLS is the fact that the theory behind this method is based on the assumption that the weights are known exactly. However, it should be noted that in this study, the variance of each observation (i.e., standard error of each CMF) is estimated and given based on empirical analysis. In the weighted linear regression model under the assumption of non-constant variance, we let

$$Y_i = \alpha + \beta X_i + \epsilon_i \qquad (8\text{-}1)$$

Where,

α=constant,

β = coefficient of parameter x,

ϵ_i= iid normal random variables with mean zero.

And, non-constant variance-covariance matrix can be

$$\begin{pmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_n^2 \end{pmatrix} \quad (8\text{-}2)$$

If we define the reciprocal of each variance, σ_i^2, as the weight, $w_i = {}^{1}/_{\sigma_i^2}$, then let matrix W be a diagonal matrix as follow:

$$W = \begin{pmatrix} w_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_i \end{pmatrix} \quad (8\text{-}3)$$

The weighted least squares estimate is then

$$\hat{\beta} = \arg\min_{\beta} \sum_{i=1}^{n} \epsilon_i^{*2} = (X^T W X)^{-1} X^T W y \quad (8\text{-}4)$$

The adjustment functions were developed using both simple linear and weighted linear regression models and compared. The ratio (i.e., adjustment factor) between actual CMF and combined CMF using the HSM combining method is predicted using various information parameters (i.e., explanatory variables) from Table 3 in the developed adjustment function.

8.1.3 Analytic Hierarchy Process

The analytic hierarchy process (AHP) introduced by Saaty (1977 and 1994) is one of the well-known multi-criteria decision-making (MCDM) approaches. The AHP is an effective approach in dealing with multi-criteria decision problems when the criteria are expressed in different units or the pertinent data are difficult to be quantified (Park et al., 2013). Generally, the AHP is used to solve complex decision problems and it uses a multi-level hierarchical structure of objectives, criteria, alternatives, etc. The pertinent data are derived by using a set of pairwise comparisons. These comparisons are used to obtain the weights of importance of the decision criteria, and the relative performance measures of the alternatives in terms of each individual decision criterion. If the comparisons are not perfectly consistent, then it provides a mechanism for improving consistency (Triantaphyllou and Mann, 1995). It should be noted that there were some criticism on the original AHP from both theoretical and practical aspects. The AHP may reverse the ranking of the alternatives when an alternative identical to one of the already existing alternatives is introduced. In order to overcome this deficiency, Belton and Gear (1983) proposed the revised-AHP that each column of the AHP decision matrix to be divided by the maximum entry of that column. Based on this proposed approach, Saaty (1994) suggested Ideal Mode AHP.

The structure of the multi-criteria decision problem can be represented in following decision matrix as below:

$$\begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_N \\ & W_1 & W_2 & \cdots & W_N \\ \hline A_1 & a_{11} & a_{12} & \cdots & a_{1N} \\ A_2 & a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_M & a_{M1} & a_{M2} & \cdots & a_{MN} \end{array} \tag{8-5}$$

Where,

A_M=alternatives,

C_N=decision criteria,

a_{ij}=performance value of the i-th alternative in terms of the j-th criterion (i=1,2,…,M, and j=1,2,…,N),

W_N=weight of the criterion C_N

In the AHP, an approach based on pairwise comparisons (Saaty, 1980) has been widely used to determine the relative importance of each alternative in terms of each criterion involved in a given decision making process. He suggested 9 as the upper limit and 1 as the lower limit. For example, if the scale has 9 as the highest alternative, the pairwise comparisons are members of the set of relative importances as follow: 9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 (Triantaphyllou and Mann, 1995). It should be noted that in this study, various pairwise comparisons based on different upper limits were applied to identify the best fitted estimates. In order to estimate priority parameters based on the relative importances implied by the pairwise comparisons in the AHP, the right principal eigenvector needs to be calculated (Saaty, 1994). It should be mentioned that each combining CMF method (from Table 8-1) and various performance measures were used as an alternative and decision criterion in the AHP, respectively.

8.2 Data Preparation

Various combinations of CMFs for single and multiple treatments from Phase I and Phase II were organized as shown in Table 8-2.

Table 8-2: Developed CMFs for Various Single Treatments and Combinations Based on Different Roadway Types and Conditions

(a) Shoulder rumble strips and widening shoulder width on rural multilane divided roadways

				First Treatment			Second Treatment (Less effective)			Combination		Specific Roadway Characteristics
No.	Road Type	Crash Type	Severity	Treatment	Method	CMF	Treatment	Method	CMF	Method	CMF	
1	Rural multilane divided roadway	All	KABCO	SRS	EB	0.76**	WSW	EB	0.77**	EB	0.61**	Original shoulder width: 4 to 12 ft
2		All	KABC	SRS	EB	0.64**	WSW	EB	0.69**	CG	0.66**	
3		SVROR	KABCO	WSW	EB	0.61**	SRS	CG	0.65**	EB	0.54**	
4		SVROR	KABC	WSW	EB	0.57**	SRS	CG	0.63**	CG	0.61**	
5		All	KABCO	SRS	EB	0.61**	WSW	EB	0.62**	EB	0.35**	Original shoulder width: 4 to 6 ft
6		All	KABC	WSW	EB	0.50**	SRS	EB	0.57**	EB	0.45**	
7		All	KABCO	SRS	EB	0.79**	WSW	EB	0.81**	EB	0.81*	Original shoulder width: 8 to 12 ft

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: SRS=shoulder rumble strips, WSW=widening shoulder width

(b) Decreasing driveway and pole densities, and increasing distances to pole and trees on rural multilane undivided roadways

					First Treatment		Second Treatment		Third Treatment		Fourth Treatment		Combinations
No.	Road Type	Crash Type	Severity	Method	Treat-ment	CMF	Treat-ment	CMF	Treat-ment	CMF	Treat-ment	CMF	CMF
8	Rural 4-lane undivided roadway	All	KABCO	CS	DD	0.69**	PD	0.85**	-	-	-	-	0.68**
9		All	KABCO		DD	0.69**	DP	0.89	-	-	-	-	0.67
10		All	KABCO		DD	0.69**	DT	0.90	-	-	-	-	0.58**
11		All	KABCO		DD	0.69**	PD	0.85**	DT	0.90	-	-	0.57**
12		All	KABCO		DD	0.69**	PD	0.85**	DP	0.89	DT	0.90	0.56**

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: DD=decreasing driveway density, PD=decreasing roadside pole density, DP=increasing distance to roadside pole, DT=increasing distance to roadside tree

(c) Shoulder rumble strips and widening shoulder width on rural two-lane roadways

				First Treatment			Second Treatment (Less effective)			Combination		Specific Roadway Characteristics
No.	Road Type	Crash Type	Severity	Treatment	Method	CMF	Treatment	Method	CMF	Method	CMF	
13	Rural two-lane roadway	All	KABCO	SRS	EB	0.83**	WSW	EB	0.87**	EB	0.75**	Original shoulder width: 2 to 12 ft
14		All	KABC	SRS		0.84*	WSW		0.89**		0.78*	
15		SVROR	KABCO	SRS		0.75*	WSW		0.82*		0.68*	
16		SVROR	KABC	SRS		0.80	WSW		0.87		0.75	
17		All	KABCO	WSW		0.70*	SRS		0.76*		0.55**	Original shoulder width: 2 ft
18				WSW		0.73	SRS		0.77		0.60**	Original shoulder width: 4 ft
19				WSW		0.75**	SRS		0.82**		0.70**	Original shoulder width: 6 ft
20				WSW		0.85	SRS		0.85*		0.80	Original shoulder width: 8 ft
21				SRS		0.86	WSW		0.88		0.82	Original shoulder width: 10 ft
22				SRS		0.88	WSW		0.90		0.84	Original shoulder width: 12 ft
23		All	KABC	WSW		0.68*	SRS		0.77*		0.54**	Original shoulder width: 2 ft
24				WSW		0.69	SRS		0.79		0.59*	Original shoulder width: 4 ft
25				WSW		0.73**	SRS		0.83**		0.70**	Original shoulder width: 6 ft
26				WSW		0.86	SRS		0.86*		0.81	Original shoulder width: 8 ft
27				SRS		0.88	WSW		0.90		0.84	Original shoulder width: 10 ft
28				SRS		0.88	WSW		0.93		0.88	Original shoulder width: 12 ft
29		SVROR	KABCO	WSW		0.64	SRS		0.65		0.43**	Original shoulder width: 2 ft
30				WSW		0.65	SRS		0.72		0.49**	Original shoulder width: 4 ft
31				WSW		0.72*	SRS		0.73*		0.57*	Original shoulder width: 6 ft
32				SRS		0.79	WSW		0.82*		0.70	Original shoulder width: 8 ft
33				SRS		0.81	WSW		0.85		0.75	Original shoulder width: 10 ft
34				SRS		0.82	WSW		0.88		0.80	Original shoulder width: 12 ft

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: SRS=shoulder rumble strips, WSW=widening shoulder width

(d) Adding thru lane, narrowing median and shoulder widths on urban arterials

				First Treatment			Second Treatment			Third Treatment			Combinations	
No.	Road Type	Crash Type	Severity	Treat-ment	Method	CMF	Treat-ment	Method	CMF	Treat-ment	Method	CMF	Method	CMF
35	Urban arterials	All	KABCO	TL	EB	0.83*	NSW	CS	1.17**	-	-	-	EB	0.93
36		All	KABC	TL		0.74*	NSW		1.15**	-	-	-		0.86
37		All	KABCO	TL		0.83*	NMW		1.08**	-	-	-		0.85
38		All	KABC	TL		0.74*	NMW		1.09**	-	-	-		0.75*
39		All	KABCO	TL		0.83*	NMW		1.08**	NSW	CS	1.17**		0.95
40		All	KABC	TL		0.74*	NMW		1.09**	NSW	CS	1.15**		0.87

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: TL=adding a thru lane, NSW=narrowing shoulder width, NMW=narrowing median width

(e) Shoulder rumble strips and widening shoulder width on rural multilane divided roadways

				First Treatment			Second Treatment (Less effective)			Combination		Specific Roadway Characteristics
No.	Road Type	Crash Type	Severity	Treatment	Method	CMF	Treatment	Method	CMF	Method	CMF	
41	Urban arterials	All	KABCO	LR	CS	0.51**	Bike	EB	0.83**	CS	0.41**	-

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: LR=lane reduction, Bike=adding a bike lane

(f) Install roadside barriers and widening shoulder width on freeways

				First Treatment			Second Treatment (Less effective)			Combination		Specific Roadway Characteristics
No.	Road Type	Crash Type	Severity	Treatment	Method	CMF	Treatment	Method	CMF	Method	CMF	
42	Freeways	All	KAB	RB	EB	0.82**	WSW	CS	0.87*	CS	0.80*	-
43		ROR	KABC	WSW	CS	0.79**	RB	EB	0.84**	CS	0.67**	-
44		ROR	KAB	RB	EB	0.74**	WSW	CS	0.80*	CS	0.70**	-

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level
Note: RB=install roadside barrier, WSW=widening shoulder width

In order to develop an adjustment function that can be applied more generally, the ratio between actual CMFs and combined CMFs using the HSM combining method (i.e., Method 1) was calculated for each combination of CMFs for single and multiple treatments. A variety of parameters of information of each combination were also obtained and Table 8-3 provides descriptive statistics of the data.

Table 8-3: Descriptive Statistics of Organized Data for Analysis

Variable	Mean	S.D.	Min.	Max.
Ratio between actual CMFs and combined CMFs using method 1 (HSM method)	1.104	0.161	0.905	1.699
Average of mean AADT value for CMF studies (veh/day)	17511.06	15323.31	4955.5	60135.5
Difference between mean AADT value for CMF studies (veh/day)	2450.34	2074.27	0	6280
CMF for first treatment (most effective CMF)	0.742	0.096	0.5	0.88
Average of standard error for CMFs	0.105	0.062	0.049	0.309
Severity	CMF for KABC and KAB severity levels = 17 samples, CMF for KABCO crashes = 27 samples			
Numbers of treatment	two single treatments = 40 samples, 3 or more single treatments = 4 samples			
High CMF for first treatment	CMF ≥ 0.8 = 14 samples, CMF < 0.8 = 30 samples			
Low CMF for first treatment	CMF ≤ 0.6 = 8 samples, CMF > 0.6 = 36 samples			
Negative CMF	at least one CMF is 1 or higher than 1 = 6 samples, all CMFs are lower than 1 = 38 samples			
Roadway type	freeway and rural divided multilane roadway = 10 samples, rural two-lane and undivided 4-lane roadway and urban arterials = 34 samples			

8.3 Analysis Results

8.3.1 Development of Adjustment Function

As described in the previous section, development of more general adjustment function is required to apply Method 7 to combine multiple CMFs. Table 8-4 presents the developed adjustment functions using simple linear and weighted regression models to modify Method 7. It was found that the weighted regression model shows better model fit than the simple linear regression since it considered the non-constant variance of each observation. The results also showed that the developed adjustment function can account for 1) different severity levels, 2) relatively higher CMF value, 3) negative safety effectiveness of treatment (i.e., CMF>1), and 4) different roadway types in combining multiple CMFs process.

Table 8-4: Development of Adjustment Function for Updating Method 7

	Multiple linear regression			Weighted multiple linear regression		
Parameter	Coeffi-cient	SE	p-value	Coeffi-cient	SE	p-value
Constant	1.6345	0.2105	<0.0001	1.6450	0.2140	<0.0001
Severity (1: KABC and KAB, 0: KABCO)	0.0594	0.0387	0.1333	0.0591	0.0397	0.1455
High CMF (1: CMF for first treatment is higher than 0.8, 0: others)	0.0877	0.0582	0.1402	0.1080	0.0584	0.0724
Negative CMF (1: at least one CMF in analysis ≥ 1.0, 0: others)	-0.1265	0.0547	0.0263	-0.1195	0.0653	0.0752
Roadway type (1: freeway and rural divided multilane roadway, 0: others)	0.1405	0.0483	0.0060	0.1827	0.0514	0.0010
CMF value for first treatment (most effective)	-0.8066	0.2994	0.0105	-0.8453	0.3060	0.0088
Root MSE	0.1196			0.0377		
R-Square	0.5129			0.5571		
Adj. R-Square	0.4489			0.4988		

8.3.2 Calculation of Combined CMFs and Comparison of Existing Combining Methods

The existing combining methods (including modified Method 7) in Table 8-1 were applied to evaluate combined CMFs. Table 8-5 shows the results of different performance measures (i.e., criteria) based on comparison between the combined CMFs using existing combining methods and the actual calculated CMFs for multiple treatments. Note that Methods 8 and 9 could not be compared because specific combinations of existing methods are not suggested for both methods. Four different performance measures (i.e., mean absolute deviation (MAD), mean absolute percentage error (MAPE), number of times selected as the best method, and number of times selected as the second best method) were applied to compare the performance of the existing combining methods. It is widely known that the MAD and MAPE statistics are used to compare the fits obtained by different forecasting or prediction methods. Smaller values indicate a better fitting result for both approaches. The MAD expresses an accuracy in the same units as the data, which helps to conceptualize the amount of error. It can be calculated by Equation (8-6) as below:

$$MAD = \frac{\sum_{t=1}^{n} |(y_t - \hat{y}_t)|}{n} \tag{8-6}$$

Where,

y_t=the actual value

$\hat{y}_t$=the fitted value

n=number of observations (t=1,2,…,n)

The MAPE measures an accuracy as a percentage of the error. Since this number is a percentage, it can be easier to understand than the other statistics. The equation is:

$$MAPE = \frac{\sum_{t=1}^{n} |(y_t - \hat{y}_t)/y_t|}{n} \times 100, (y_t \neq 0) \quad (8\text{-}7)$$

Moreover, Park et al., (2014) used the number of times selected as the best and the second best methods as one of the measures to compare the results by existing combining methods. These measures are not very informative, but it still can compare the performances of predictive methods through a simple comparison.

The results showed that Method 3 produces the most accurate combined CMF values among 7 methods. Also, it can be concluded that Method 2 and Method 7 perform as the second best and third best methods for combining CMFs based on the comparison results. It is worth mentioning that in Table 8-5, the rankings of combining methods for each performance measure were also found for the pairwise comparisons in the AHP.

Table 8-5: Comparison of Calculated Combined CMFs using Existing Methods and Actual Safety Effects for Multiple Treatments

	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7
Statistical test to compare combined values with actual safety effects							
MAD (Ranking)	0.0674 (4th)	0.0422 (1st)	0.0428 (2nd)	0.0764 (5th)	0.0807 (6th)	0.1671 (7th)	0.0448 (3rd)
MAPE (Ranking)	10.1% (4th)	7.1% (2nd)	6. 8% (1st)	13.4% (5th)	13.8% (6th)	25.7% (7th)	7.4% (3rd)
Number of times to be selected as the best and second best fitted existing method (out of 44)							
Best fitted (Ranking)	8 (4th)	9 (2nd)	9 (2nd)	3 (5th)	2 (7th)	3 (5th)	10 (1st)
Second best (Ranking)	2 (6th)	12 (2nd)	17 (1st)	3 (5th)	4 (4th)	0 (7th)	5 (3rd)

8.3.3 Development of Alternative Combining Approach

Since the best, second best, and third best fitted combining methods were identified in the previous section, Method 8 and Method 9 can be modified and used to evaluate the combined CMFs for multiple treatments. However, it should be mentioned that the approach of averaging 2 or 3 combining methods is still a simple calculation and does not guarantee reliable results. Therefore, Method 10 and Method 11 are suggested in this study as the modified versions of Method 8 and Method 9 based on the priority parameters from the AHP as shown in Table 8-6. The calculated priority parameters to weight the combining methods for Method 10 and Method 11 are presented in Table 8-7. It should be noted that in this study, the weight of each criterion was assumed to be evenly given in the AHP. Moreover, it should be mentioned that various averaging approaches (e.g., averaging 4 to 7 combining methods) with calculation of priority factors from the AHP based on the different upper limits in pairwise comparisons were also conducted but the approaches did not produce better estimates than the existing combining methods.

Table 8-6: Suggestion of New Combining Methods

No.	Methods	Description
10	$CMF_t = w * CMF_x + (1 - w) * CMF_y$ CMF_t = Adjusted CMF for the combined treatments CMF_x =combined CMF from the method 2 CMF_y = combined CMF from the method 3 w = Priority (weighting) parameter from multi-criteria decision making process w = 0.46	Average the existing combining method 2 and 3 based on weighting parameters from analytic hierarchy process
11	$CMF_t = w_1 * CMF_x + w_2 * CMF_y + (1 - w_1 - w_2) * CMF_z$ CMF_t = Adjusted CMF for the combined treatments CMF_x =combined CMF from the method 2 CMF_y = combined CMF from the method 3 CMF_z = combined CMF from the method 7 w_n= Priority (weighting) parameters from multi-criteria decision making process w_1= 0.35, and w_2= 0.41	Average the existing combining method 2, 3 and 7 based on weighting parameters from analytic hierarchy process

Table 8-7: Calculated Priority Parameters for Method 10 and Method 11

(a) Priority parameters for Method 10

	Decision Criteria				Final Priority
	MAD	MAPE	Number of times selected as the best fitted method	Number of times selected as the second best fitted method	
Weight of criteria	0.25	0.25	0.25	0.25	
Method 2	0.67	0.33	0.33	0.50	0.46
Method 3	0.33	0.67	0.67	0.50	0.54

(b) Priority parameters for Method 11

	Decision Criteria				Final Priority
	MAD	MAPE	Number of times selected as the best fitted method	Number of times selected as the second best fitted method	
Weight of criteria	0.25	0.25	0.25	0.25	
Method 2	0.54	0.30	0.25	0.30	0.35
Method 3	0.30	0.54	0.25	0.54	0.41
Method 7	0.16	0.16	0.50	0.16	0.25

Table 8-8 provides the predictive performances (i.e., MAD and MAPE) of Method 8, Method 9, Method 10 and Method 11 for combining multiple CMFs. The results show that Method 11 outperforms the other combining methods and provides the most reliable combined CMFs. Thus, it can be recommended to apply Method 11 to combine multiple CMFs to accurately evaluate the safety effects of multiple treatments.

Table 8-8: Predictive Performances of Modified and Suggested Combining Methods

	Method 8	Method 9	Method 10	Method 11
MAD	0.0417	0.0437	0.0417	0.0383
MAPE	6.9%	7.0%	6.8%	6.6%

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

This study develops Florida-specific CMFs for various treatments to validate the CMFs provided in the HSM. The study also develops CMFs for the other treatments not included in the HSM. In phases I and II, a total of 54 treatments for roadway segments, intersections and special facilities were considered. For this task, extensive data were collected from multiple data sources maintained by FDOT including multi-year road geometry inventory (i.e., RCI) and crash database (i.e., CARS). In order to estimate CMFs, the observational before-after and cross-sectional studies were utilized for different crash types and injury levels. For any given treatment, only the CMF with lowest standard error was selected as the Florida-specific CMF among various CMFs estimated using different methods.

In general, Florida-specific CMFs reflect similar safety effectiveness as the CMFs in the HSM for most treatments. Florida-specific CMFs are also generally statistically significant at a 90% confidence level. These CMFs are recommended for application to Florida as they better reflect local conditions in Florida compared to the HSM. However, for the treatments with unknown safety effectiveness in Florida as indicated by statistically insignificant Florida-specific CMFs, the CMFs in the HSM (if they are statistically significant) are recommended. Florida-specific CMFs for the treatments not included in the HSM are also statistically significant at a 95% confidence level. The recommended CMFs (including CMFs calculated from CMFunctions) in Florida for all the treatments are summarized in Chapter 10 which is a Florida CMF Manual.

Although Florida-specific CMFs have been developed through the two phases of this study, there are no Florida-specific base SPFs to predict the expected crash frequency of base roadway condition. It is suggested to calculate a calibration factor and multiply it to the base SPF when users apply the SPF in HSM to their region. However, calculation of calibration factor (ratio of observed and predicted crashes) is not a scientific way and many researchers claimed that it does not guarantee reliable results. Moreover, in order to help users understand how to apply the SPFs and CMFs in the HSM parts C and D easily, NCHRP Project 17-38 research team has provided a set of training spreadsheets. However, since the spreadsheets are developed based on the HSM, it is still difficult for safety practitioners in Florida to learn the applications of the predictive procedure to their specific region. Thus, there is still a need to develop complete Florida-specific SPFs/CMFs manual with implementation training tools for safety professionals.

CHAPTER 10. RECOMMENDED FLORIDA-SPECIFIC CRASH MODIFICATION FACTORS (FL CMF MANUAL)

10.1 Roadway Segments

10.1.1 Rural Two-lane Roadways

Table 10-1: CMFs for *Adding a Through Lane*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Two-lane undivided roadways)	All types (KABCO)	**0.71**	**0.09**
	All types (KABC)	**0.51**	**0.07**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-2: CMFs for *Adding Shoulder Rumble Strips*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Two-lane undivided roadways)	All types (KABCO)	**0.83**	**0.07**
	All types (KABC)	**0.84**	**0.08**
	SVROR (KABCO)	**0.75**	**0.14**
	SVROR (KABC)	0.80	0.16

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-3: CMFs for *Widening Shoulder Width*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Two-lane undivided roadways)	All types (KABCO)	**0.87**	**0.05**
	All types (KABC)	**0.89**	**0.06**
	SVROR (KABCO)	**0.82**	**0.10**
	SVROR (KABC)	0.87	0.12

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-4: CMFs for *Adding Shoulder Rumble Strips + Widening Shoulder Width*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Two-lane undivided roadways)	All types (KABCO)	**0.75**	**0.10**
	All types (KABC)	**0.78**	**0.11**
	SVROR (KABCO)	**0.68**	**0.17**
	SVROR (KABC)	0.75	0.21

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-5: CMFs for *Adding Shoulder Rumble Strips* Based on Different Shoulder Width (from CMFunction)

Setting (Road Type)	Crash Type (Severity)	Original Shoulder Width					
		2 ft	4 ft	6 ft	8 ft	10 ft	12 ft
		CMF					
Rural (Two-lane undivided roadways)	All types (KABCO)	0.76	0.77	0.82	0.85	0.86	0.88
	All types (KABC)	0.77	0.79	0.83	0.86	0.88	0.88
	SVROR (KABCO)	0.65	0.72	0.73	0.79	0.81	0.82

Table 10-6: CMFs for *Widening Shoulder Width* Based on Different Shoulder Width (from CMFunction)

Setting (Road Type)	Crash Type (Severity)	Original Shoulder Width					
		2 ft	4 ft	6 ft	8 ft	10 ft	12 ft
		CMF					
Rural (Two-lane undivided roadways)	All types (KABCO)	0.70	0.73	0.75	0.85	0.88	0.90
	All types (KABC)	0.68	0.69	0.73	0.86	0.90	0.93
	SVROR (KABCO)	0.64	0.65	0.72	0.82	0.85	0.88

Table 10-7: CMFs for *Adding Shoulder Rumble Strips + Widening Shoulder Width* Based on Different Shoulder Width (from CMFunction)

Setting (Road Type)	Crash Type (Severity)	Original Shoulder Width					
		2 ft	4 ft	6 ft	8 ft	10 ft	12 ft
		CMF					
Rural (Two-lane undivided roadways)	All types (KABCO)	0.55	0.60	0.70	0.80	0.82	0.84
	All types (KABC)	0.54	0.59	0.70	0.81	0.84	0.88
	SVROR (KABCO)	0.43	0.49	0.57	0.70	0.75	0.80

Table 10-8: CMFs for *Changing Lane Width* at Non-Curved Segments (from CMFunction)

Rural (Two-lane undivided roadways)	All types (KABCO)		All types (KABC)		All types (KABC)	
	CMF	S.E	CMF	S.E	CMF	S.E
AADT= 3,000						
12 to 10 ft	**1.25**	**0.02**	**1.23**	**0.02**	**1.22**	**0.02**
12 to 10.5 ft	**1.18**	**0.01**	**1.17**	**0.01**	**1.16**	**0.01**
12 to 11 ft	**1.12**	**0.01**	**1.11**	**0.01**	**1.10**	**0.01**
12 to 11.5 ft	**0.93**	**0.01**	**0.93**	**0.01**	**0.93**	**0.01**
Base: 12 ft	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	**1.02**	**0.01**	**1.02**	**0.01**	**1.02**	**0.01**
12 to 13 ft	**0.63**	**0.02**	**0.65**	**0.02**	**0.66**	**0.02**
12 to 13.5 ft	**0.50**	**0.02**	**0.53**	**0.02**	**0.53**	**0.03**
12 to 14 ft	**0.39**	**0.02**	**0.42**	**0.03**	**0.43**	**0.03**
AADT= 15,000						
12 to 10 ft	**1.30**	**0.02**	**1.28**	**0.02**	**1.27**	**0.02**
12 to 10.5 ft	**1.22**	**0.01**	**1.20**	**0.01**	**1.19**	**0.01**
12 to 11 ft	**1.14**	**0.01**	**1.13**	**0.01**	**1.13**	**0.01**
12 to 11.5 ft	**0.92**	**0.01**	**0.92**	**0.01**	**0.92**	**0.01**
Base: 12 ft	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	**1.03**	**0.01**	**1.03**	**0.01**	**1.03**	**0.01**
12 to 13 ft	**0.57**	**0.02**	**0.60**	**0.02**	**0.60**	**0.02**
12 to 13.5 ft	**0.43**	**0.02**	**0.46**	**0.02**	**0.47**	**0.02**
12 to 14 ft	**0.32**	**0.02**	**0.36**	**0.02**	**0.37**	**0.02**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-9: CMFs for *Changing Shoulder Width* at Non-Curved Segments (from CMFunction)

Rural (Two-lane undivided roadways)	All types (KABCO)		All types (KABC)		All types (KABC)	
	CMF	S.E	CMF	S.E	CMF	S.E
			AADT= 3,000			
6 to 4 ft	**1.36**	**0.01**	**1.38**	**0.01**	**1.39**	**0.01**
6 to 4.5 ft	**1.26**	**0.01**	**1.27**	**0.01**	**1.28**	**0.01**
6 to 5 ft	**1.17**	**0.01**	**1.18**	**0.01**	**1.18**	**0.01**
6 to 5.5 ft	**1.08**	**0.01**	**1.08**	**0.01**	**1.09**	**0.01**
Base: 6 ft	1.00	-	1.00	-	1.00	-
6 to 6.5 ft	**0.93**	**0.01**	**0.92**	**0.01**	**0.92**	**0.01**
6 to 7 ft	**0.86**	**0.01**	**0.85**	**0.01**	**0.85**	**0.01**
6 to 7.5 ft	**0.80**	**0.01**	**0.79**	**0.01**	**0.78**	**0.01**
6 to 8 ft	**0.74**	**0.01**	**0.73**	**0.01**	**0.72**	**0.01**
			AADT= 15,000			
6 to 4 ft	**1.44**	**0.01**	**1.47**	**0.01**	**1.49**	**0.01**
6 to 4.5 ft	**1.32**	**0.01**	**1.34**	**0.01**	**1.35**	**0.01**
6 to 5 ft	**1.20**	**0.01**	**1.21**	**0.01**	**1.22**	**0.01**
6 to 5.5 ft	**1.10**	**0.01**	**1.10**	**0.01**	**1.10**	**0.01**
Base: 6 ft	1.00	-	1.00	-	1.00	-
6 to 6.5 ft	**0.91**	**0.01**	**0.91**	**0.01**	**0.91**	**0.01**
6 to 7 ft	**0.83**	**0.01**	**0.82**	**0.01**	**0.82**	**0.01**
6 to 7.5 ft	**0.76**	**0.01**	**0.75**	**0.01**	**0.74**	**0.01**
6 to 8 ft	**0.69**	**0.01**	**0.68**	**0.01**	**0.67**	**0.01**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-10: CMFs for *Changing Lane Width* at Curved Segments (from CMFunction)

Rural (Two-lane undivided roadways)		CMF (S.E)			CMF (S.E)			CMF (S.E)		
		KABCO	KABC	KAB	KABCO	KABC	KAB	KABCO	KABC	KAB
		Shoulder width= 4 ft			Shoulder width= 6 ft			Shoulder width= 8 ft		
		AADT= 3,000								
12 to 10ft	CMF	1.18**	1.16**	1.16**	1.15**	1.13*	1.13*	1.12*	1.10	1.10
	S.E	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07
12 to 10.5ft	CMF	1.13*	1.12*	1.12*	1.11*	1.10	1.10	1.09	1.07	1.07
	S.E	0.07	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07
12 to 11ft	CMF	1.09	1.08	1.07	1.07	1.06	1.06	1.06	1.05	1.05
	S.E	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07
12 to 11.5ft	CMF	0.92*	0.92*	0.92*	0.91**	0.91**	0.92*	0.91**	0.91	0.91*
	S.E	0.04	0.04	0.05	0.04	0.04	0.05	0.04	0.04	0.05
Base: 12ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
12 to 12.5ft	CMF	1.04	1.04	1.03	1.05	1.05	1.04	1.05	1.05	1.05
	S.E	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
12 to 13ft	CMF	0.65**	0.67**	0.67**	0.65**	0.68**	0.68**	0.66**	0.69**	0.69**
	S.E	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12 to 13.5ft	CMF	0.52**	0.55**	0.55**	0.53**	0.56**	0.56**	0.54**	0.57**	0.57**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12 to 14ft	CMF	0.42**	0.45**	0.45**	0.43**	0.46**	0.47**	0.44**	0.47**	0.48**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Shoulder width= 4 ft			Shoulder width= 6 ft			Shoulder width= 8 ft		
		AADT= 15,000								
12 to 10ft	CMF	1.24**	1.21**	1.21**	1.20**	1.18**	1.18**	1.17**	1.15*	1.15*
	S.E	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.08
12 to 10.5ft	CMF	1.17**	1.15**	1.15**	1.15**	1.13*	1.13*	1.13*	1.11	1.11
	S.E	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
12 to 11ft	CMF	1.11*	1.10*	1.10	1.10*	1.08	1.08	1.08	1.07	1.07
	S.E	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.06	0.07
12 to 11.5ft	CMF	0.90**	0.91**	0.91*	0.90**	0.91**	0.91**	0.89**	0.89**	0.90**
	S.E	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Base: 12ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
12 to 12.5ft	CMF	1.04	1.04	1.04	1.05	1.05	1.05	1.06	1.06	1.05
	S.E	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
12 to 13ft	CMF	0.59**	0.61**	0.62**	0.60**	0.62**	0.63**	0.60**	0.63**	0.64**
	S.E	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12 to 13.5ft	CMF	0.45**	0.48**	0.49**	0.46**	0.49**	0.50**	0.47**	0.50**	0.51**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12 to 14ft	CMF	0.35**	0.38**	0.38**	0.35**	0.39**	0.39**	0.36**	0.40**	0.40**
	S.E	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

Table 10-11: CMFs for *Changing Shoulder Width* at Curved Segments (from CMFunction)

Rural (Two-lane undivided roadways)		CMF (S.E)			CMF (S.E)			CMF (S.E)		
		KABCO	KABC	KAB	KABCO	KABC	KAB	KABCO	KABC	KAB
		Lane width= 10 ft			Lane width= 12 ft			Lane width= 14 ft		
		AADT= 3,000								
6 to 4 ft	CMF	1.19**	1.20**	1.23**	1.16**	1.17**	1.20**	1.13**	1.13**	1.17**
	S.E	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
6 to 4.5 ft	CMF	1.14**	1.14**	1.17**	1.12**	1.12**	1.15**	1.10**	1.10**	1.12**
	S.E	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03
6 to 5 ft	CMF	1.09**	1.09**	1.11**	1.08**	1.08**	1.10**	1.06**	1.06**	1.08**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
6 to 5.5 ft	CMF	1.04	1.05*	1.05*	1.04	1.04	1.05*	1.03	1.03	1.04
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Base: 6 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
6 to 6.5 ft	CMF	0.96	0.96	0.95*	0.96	0.96	0.96	0.97	0.97	0.96
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7 ft	CMF	0.92**	0.91**	0.90**	0.93**	0.93**	0.91**	0.94**	0.94**	0.92**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7.5 ft	CMF	0.88**	0.87**	0.86**	0.90**	0.89**	0.87**	0.91**	0.91**	0.89**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 8 ft	CMF	0.84**	0.84**	0.81**	0.86**	0.86**	0.83**	0.89**	0.88**	0.85**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
		Lane width= 10 ft			Lane width= 12 ft			Lane width= 14 ft		
		AADT= 15,000								
6 to 4 ft	CMF	1.27**	1.28**	1.31**	1.23**	1.24**	1.28**	1.20**	1.21**	1.25**
	S.E	0.02	0.02	0.03	0.02	0.02	0.03	0.02	10.02	0.03
6 to 4.5 ft	CMF	1.19**	1.20**	1.23**	1.17**	1.18**	1.20**	1.15**	1.15**	1.18**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
6 to 5 ft	CMF	1.12**	1.13**	1.15**	1.11**	1.11**	1.13**	1.10**	1.10**	1.12**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 5.5 ft	CMF	1.06**	1.06**	1.07**	1.05*	1.06**	1.06**	1.05*	1.05*	1.06**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Base: 6 ft	CMF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	S.E	-	-	-	-	-	-	-	-	-
6 to 6.5 ft	CMF	0.94**	0.94**	0.93**	0.95*	0.95*	0.94**	0.96	0.95	0.95*
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7 ft	CMF	0.89**	0.88**	0.87**	0.90**	0.90**	0.88**	0.91**	0.91**	0.89**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 7.5 ft	CMF	0.84**	0.83**	0.81**	0.85**	0.85**	0.83**	0.87**	0.87**	0.85**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
6 to 8 ft	CMF	0.79**	0.78**	0.76**	0.81**	0.80**	0.78**	0.83**	0.83**	0.80**
	S.E	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

**: Significant at a 95% confidence level, *: Significant at a 90% confidence level

10.1.2 Rural Multilane Roadways

Table 10-12: **CMFs for *Adding Shoulder Rumble Strips* Based on Different Speed Limit Ranges**

Setting (Road Type)	Crash Type (Severity)	Speed Limit (mph)	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	45~70	**0.76**	**0.07**
		65~70	**0.73**	**0.07**
	All types (KABC)	45~70	**0.64**	**0.09**
		65~70	**0.63**	**0.09**
	SVROR (KABCO)	45~70	**0.60**	**0.09**
		65~70	**0.58**	**0.09**
	SVROR (KABC)	45~70	**0.64**	**0.15**
		65~70	**0.59**	**0.14**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-13: **CMFs for *Widening Shoulder Width* Based on Different Speed Limit Ranges**

Setting (Road Type)	Crash Type (Severity)	Speed Limit (mph)	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	45~70	**0.88**	**0.04**
		65~70	**0.66**	**0.12**
	All types (KABC)	45~70	**0.82**	**0.05**
		65~70	**0.51**	**0.13**
	All types (KAB)	45~70	**0.79**	**0.06**
	SVROR (KABCO)	45~70	**0.75**	**0.08**
		65~70	**0.60**	**0.20**
	SVROR (KABC)	45~70	**0.72**	**0.10**
		65~70	**0.39**	**0.19**
	SVROR (KAB)	45~70	**0.69**	**0.11**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-14: **CMFs for *Adding Shoulder Rumble Strips + Widening Shoulder Width* Based on Different Speed Limit Ranges**

Setting (Road Type)	Crash Type (Severity)	Speed Limit (mph)	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	45~70	**0.50**	**0.06**
		65~70	**0.48**	**0.06**
	All types (KABC)	45~70	**0.66**	**0.11**
		65~70	**0.63**	**0.11**
	SVROR (KABCO)	45~70	**0.40**	**0.08**
		65~70	**0.40**	**0.08**
	SVROR (KABC)	45~70	**0.63**	**0.15**
		65~70	**0.58**	**0.15**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-15: **CMFs for *Adding Shoulder Rumble Strips* Based on Different Original Shoulder Width**

Setting (Road Type)	Crash Type (Severity)	Shoulder Width	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	4 to 6 ft	**0.61**	**0.10**
	All types (KABC)		**0.57**	**0.14**
	All types (KABCO)	8 to 12 ft	**0.79**	**0.06**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-16: **CMFs for *Widening Shoulder Width* Based on Different Original Shoulder Width**

Setting (Road Type)	Crash Type (Severity)	Shoulder Width	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	4 to 6 ft	**0.62**	**0.08**
	All types (KABC)		**0.50**	**0.08**
	All types (KABCO)	8 to 12 ft	**0.81**	**0.07**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-17: **CMFs for *Adding Shoulder Rumble Strips + Widening Shoulder Width* Based on Different Original Shoulder Width**

Setting (Road Type)	Crash Type (Severity)	Shoulder Width	CMF	Std. Error
Rural (Multilane highways)	All types (KABCO)	4 to 6 ft	**0.35**	**0.06**
	All types (KABC)		**0.45**	**0.11**
	All types (KABCO)	8 to 12 ft	**0.81**	**0.09**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-18: **CMFs for *Widening Shoulder Width based on Different Roadway Conditions* (from CMFunctions)**

Setting (Road Type)	Crash Type (Severity)	Different Original Shoulder Width				Different Actual Widened Width			
		2 ~ 8 ft		9 ~ 12 ft		1 ~ 4 ft		5 ~ 10 ft	
		CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
Rural (Multilane highways)	All (KABCO)	0.72**	0.07	0.94	0.05	0.94	0.07	0.85**	0.05
	All (KABC)	0.73**	0.09	0.84**	0.06	0.85*	0.09	0.80**	0.06
	All (KAB)	0.69**	0.12	0.82**	0.08	0.84	0.12	0.77**	0.08
	ROR (KABCO)	0.66**	0.15	0.77**	0.09	0.77*	0.14	0.74**	0.09
	ROR (KABC)	0.62**	0.18	0.74**	0.11	0.73	0.17	0.71**	0.12
	ROR (KAB)	0.57**	0.19	0.73*	0.14	0.71	0.21	0.68**	0.13

**: significant at a 95% confidence level, *: significant at a 90% confidence level

Table 10-19: CMFs for *Adding a Raised Median*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Multilane highways)	All types (KABC)	**0.76**	**0.12**
	All types (O)	**0.75**	**0.11**
	Head-on (KABCO)	**0.29**	**0.20**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-20: CMFs for *Narrowing Paved Right Shoulder Width*

Shoulder Width	Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
8 to 6-ft Conversion	Rural (Multilane)	All types (KABCO)	**1.16**	**0.05**
8 to 4-ft Conversion			**1.35**	**0.06**
8 to 2-ft Conversion			**1.57**	**0.07**
8 to 0-ft Conversion			**1.82**	**0.08**
8 to 6-ft Conversion	Rural (Multilane)	All types (KABC)	**1.17**	**0.06**
8 to 4-ft Conversion			**1.37**	**0.07**
8 to 2-ft Conversion			**1.61**	**0.08**
8 to 0-ft Conversion			**1.88**	**0.09**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-21: CMFs for *Installation of Median Barriers*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural (Multilane roadways)	All types (KABCO)	**1.24**	**0.03**
	All types (KABC)	**0.82**	**0.08**
	All types (KAB)	**0.77**	**0.07**
	All types (KA)	**0.71**	**0.08**
	All types (K)	**0.57**	**0.10**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-22: CMFs for *Increasing Distance to Roadside Poles* (from CMFunction)

Setting (Road Type)	Increasing Distance to Poles	All (KABCO) crashes	All (KABC) crashes	ROR (KABCO) crashes
		CMF (S.E)		
Rural (Multilane undivided roadways)	1 ft (Base)	1.00 (-)	1.00 (-)	1.00 (-)
	1 ft to 2 ft	**0.86 (0.05)**	**0.90 (0.05)**	**0.78 (0.10)**
	1 ft to 3 ft	**0.75 (0.09)**	**0.80 (0.10)**	**0.61 (0.16)**
	1 ft to 4 ft	**0.64 (0.11)**	**0.72 (0.13)**	**0.47 (0.19)**
	1 ft to 5 ft	**0.56 (0.13)**	**0.64 (0.15)**	**0.37 (0.20)**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-23: CMFs for *Increasing Distance to Roadside Trees* (from CMFunction)

Setting (Road Type)	Increasing Distance to Trees	All (KABCO) crashes	
		CMF	Std. Error
Rural (Multilane undivided roadways)	1 ft (Base)	1.00 (-)	1.00 (-)
	1 ft to 2 ft	**0.97**	**0.02**
	1 ft to 3 ft	**0.94**	**0.03**
	1 ft to 4 ft	**0.92**	**0.04**
	1 ft to 5 ft	**0.89**	**0.06**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-24: CMFs for *Decreasing Density of Driveways* (from CMFunction)

Setting (Road Type)	Driveways/mile	All (KABCO) crashes	All (KABC) crashes	All (KAB) crashes	ROR (KABCO) crashes
		CMF (S.E)			
Rural (Multilane undivided roadways)	AADT= 6000 veh/day				
	70 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
	60	**0.81 (0.01)**	**0.83 (0.01)**	**0.86 (0.01)**	**0.82 (0.01)**
	50	**0.66 (0.01)**	**0.69 (0.01)**	**0.73 (0.01)**	**0.67 (0.02)**
	40	**0.53 (0.01)**	**0.58 (0.01)**	**0.63 (0.02)**	**0.55 (0.02)**
	30	**0.43 (0.01)**	**0.48 (0.02)**	**0.54 (0.02)**	**0.45 (0.02)**
	AADT= 22000 veh/day				
	70 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
	60	**0.79 (0.01)**	**0.81 (0.01)**	**0.84 (0.01)**	**0.79 (0.01)**
	50	**0.62 (0.01)**	**0.66 (0.01)**	**0.70 (0.01)**	**0.63 (0.02)**
	40	**0.49 (0.01)**	**0.53 (0.01)**	**0.58 (0.01)**	**0.50 (0.02)**
	30	**0.38 (0.01)**	**0.43 (0.01)**	**0.49 (0.02)**	**0.40 (0.02)**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-25: CMFs for *Decreasing Density of Roadside Poles* (from CMFunction)

Setting (Road Type)	Driveways/mile	All (KABCO) crashes	All (KABC) crashes	All (KAB) crashes	ROR (KABCO) crashes
		CMF (S.E)			
Rural (Multilane undivided roadways)	110 (Base)	1.00 (-)	1.00 (-)	1.00 (-)	1.00 (-)
	100	**0.82 (0.04)**	**0.84 (0.04)**	**0.81 (0.05)**	**0.82 (0.07)**
	90	**0.68 (0.07)**	**0.71 (0.07)**	**0.66 (0.08)**	**0.68 (0.13)**
	80	**0.56 (0.09)**	**0.59 (0.09)**	**0.53 (0.09)**	**0.56 (0.16)**
	70	**0.46 (0.10)**	**0.50 (0.10)**	**0.43 (0.10)**	**0.46 (0.17)**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-26: CMFs for *Changing Lane Width* on Divided and Undivided Rural Multilane Roadways (from CMFunction)

Changes of lane width	Divided				Undivided			
	KABCO		KABC		KABCO		KABC	
	CMF	S.E	CMF	S.E	CMF	S.E	CMF	S.E
AADT= 3,000								
12 to 10 ft	1.87**	0.03	2.01**	0.02	1.31**	0.05	1.42**	0.05
12 to 10.5 ft	1.60**	0.03	1.69**	0.02	1.23**	0.06	1.30**	0.05
12 to 11 ft	1.37**	0.02	1.42**	0.02	1.14**	0.06	1.19**	0.05
12 to 11.5 ft	1.17**	0.02	1.19**	0.02	1.07	0.06	1.09*	0.05
Base: 12 ft	1.00	-	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	0.86**	0.02	0.84**	0.02	0.93	0.06	0.92*	0.05
12 to 13 ft	0.73**	0.02	0.70**	0.01	0.87**	0.06	0.84**	0.05
12 to 13.5 ft	0.63**	0.02	0.59**	0.01	0.82**	0.06	0.77**	0.05
12 to 14 ft	0.53**	0.02	0.50**	0.01	0.76**	0.06	0.70**	0.04
AADT= 15,000								
12 to 10 ft	2.12**	0.02	2.32**	0.02	1.38**	0.05	1.52**	0.04
12 to 10.5 ft	1.76**	0.02	1.88**	0.02	1.28**	0.05	1.37**	0.04
12 to 11 ft	1.46**	0.02	1.52**	0.02	1.18**	0.05	1.23**	0.04
12 to 11.5 ft	1.21**	0.02	1.23**	0.01	1.08	0.05	1.11**	0.04
Base: 12 ft	1.00	-	1.00	-	1.00	-	1.00	-
12 to 12.5 ft	0.83**	0.01	0.81**	0.01	0.92	0.05	0.90**	0.04
12 to 13 ft	0.69**	0.01	0.66**	0.01	0.85**	0.05	0.81**	0.04
12 to 13.5 ft	0.57**	0.01	0.53**	0.01	0.78**	0.05	0.73**	0.04
12 to 14 ft	0.47**	0.01	0.43**	0.01	0.72**	0.05	0.66**	0.03

**: significant at a 95% confidence level, *: significant at a 90% confidence level

10.1.3 Rural / Urban Roadways

Table 10-27: CMFs for *Adding Shoulder Rumble Strips*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural/Urban (Two-lane undivided roadways)	All types (KABCO)	**0.71**	**0.10**
	All types (KABC)	0.81	0.13
	SVROR (KABCO)	**0.50**	**0.16**
	SVROR (KABC)	0.67	0.25

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-28: CMFs for *Converting a TWLTL to a Raised Median*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural/Urban (Undivided roadways)	All types (KABCO)	**0.53**	**0.02**
	All types (KABC)	**0.67**	**0.04**
	All types (Head-on)	**0.27**	**0.07**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-29: CMFs for *Adding Lighting*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Rural/Urban (All roadways)	All KABC (Injury)	**0.63**	**0.12**
	All types (O)	0.84	0.18
	All types (KAB)	0.89	0.17
	All types (KABCO)	**0.68**	**0.09**
	Rear-end (KABCO)	**0.67**	**0.14**
	Angle (KABCO)	**0.64**	**0.18**
	Single (KABCO)	**0.72**	**0.18**
	Other crash types (KABCO)	**0.72**	**0.08**

Table 10-30: CMFs for *Decreasing School Zone Speed Limits* (from CMFunction)

Setting (Road Type)	School Zone Speed Limit	All (KABCO)		All (KABC)		All (KAB)	
		CMF	S.E	CMF	S.E	CMF	S.E
Rural/Urban (All roadways)	Base: 35mph	1.00	-	1.00	-	1.00	-
	30mph	**0.77**	**0.02**	**0.75**	**0.02**	**0.72**	**0.02**
	25mph	**0.59**	**0.01**	**0.57**	**0.01**	**0.52**	**0.02**
	20mph	**0.46**	**0.01**	**0.43**	**0.01**	**0.38**	**0.01**
	15mph	**0.35**	**0.01**	**0.32**	**0.01**	**0.28**	**0.01**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

10.1.4 Urban Arterials

Table 10-31: CMFs for *Adding a Through Lane* based on Different Median Width

Setting (Road Type)	Median Width (ft)	Crash Type (Severity)	CMF	Std. Error
Urban (Two-lane undivided roadways)	all	All types (KABCO)	**0.35**	**0.09**
	all	All types (KABC)	**0.33**	**0.09**
	12-14 ft	All types (KABCO)	**0.47**	**0.23**
	20-24 ft	All types (KABCO)	**0.52**	**0.15**
	30 ft or more	All types (KABCO)	**0.28**	**0.01**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-32: CMFs for *Adding Lighting*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (4-lane/6-lane Principal and Minor Arterials)**	All types (KABC)	**0.68**	**0.05**
	All types (O)	**0.76**	**0.08**
	All types (KAB)	**0.77**	**0.09**
	All types (KABCO)	**0.74**	**0.10**
	Rear-end (KABCO)	**0.62**	**0.12**
	Angle (KABCO)	**0.82**	**0.10**
	Single (KABCO)	**0.63**	**0.09**
	Other crash types (KABCO)	**0.82**	**0.12**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-33: CMFs for *Adding a Raised Median*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Two-lane roadways)	All types (KABC)	**0.61***	**0.10***
Urban (Multilane highways)	All types (KABC)	**0.81**	**0.09**
	All types (O)	**0.74**	**0.09**
	Head-on (KABCO)	**0.32**	**0.13**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-34: CMFs for *Increasing Median Width* (from CMFunction)

Median Width	Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
10-ft to 20-ft conversion	Urban (4 lanes with Full Access Control)	All types (KABCO)	**0.86**	**0.04**
10-ft to 30-ft conversion			**0.73**	**0.06**
10-ft to 40-ft conversion			**0.63**	**0.08**
10-ft to 50-ft conversion			**0.54**	**0.09**
10-ft to 60-ft conversion			**0.46**	**0.10**
10-ft to 70-ft conversion			**0.39**	**0.10**
10-ft to 80-ft conversion			**0.34**	**0.10**
10-ft to 90-ft conversion			**0.29**	**0.10**
10-ft to 100-ft conversion			**0.25**	**0.10**
10-ft to 20-ft conversion	Urban (5 or more lanes with Full Access Control)	All types (KABCO)	**0.98**	**0.01**
10-ft to 30-ft conversion			**0.97**	**0.01**
10-ft to 40-ft conversion			**0.95**	**0.02**
10-ft to 50-ft conversion			**0.94**	**0.02**
10-ft to 60-ft conversion			**0.92**	**0.03**
10-ft to 70-ft conversion			**0.91**	**0.03**
10-ft to 80-ft conversion			**0.89**	**0.04**
10-ft to 90-ft conversion			**0.88**	**0.04**
10-ft to 100-ft conversion			**0.87**	**0.05**

Note: The CMFs in bold are statistically significant at a 95% confidence level.
These CMFs for crashes in all median types (not only traversable medians) and all crash types (not only cross-median crashes).

Table 10-35: CMFs for *Increasing Median Width* (Continued) (from CMFunction)

Median Width	Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
10-ft to 20-ft conversion	Urban (4 lanes with Partial or No Access Control)	All types (KABCO)	**0.94**	**0.03**
10-ft to 30-ft conversion			**0.89**	**0.06**
10-ft to 40-ft conversion			**0.84**	**0.09**
10-ft to 50-ft conversion			**0.79**	**0.11**
10-ft to 60-ft conversion			**0.74**	**0.13**
10-ft to 70-ft conversion			**0.70**	**0.14**
10-ft to 80-ft conversion			**0.66**	**0.16**
10-ft to 90-ft conversion			**0.62**	**0.17**
10-ft to 100-ft conversion			**0.58**	**0.18**

Note: The CMFs in bold are statistically significant at a 95% confidence level.
These CMFs for crashes in all median types (not only traversable medians) and all crash types (not only cross-median crashes).

Table 10-36: CMFs for *Lane Reduction (Converting 4 to 3 Lanes)*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Undivided arterials)	All types (KABCO)	**0.56**	**0.15**
	All types (KABC)	**0.63**	**0.17**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-37: CMFs for *Road Diet (Lane Reduction + Adding a Bike Lane)*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Undivided arterials)	All types (KABCO)	**0.41**	**0.12**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-38: CMFs for *Adding a Bike Lane*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Undivided arterials)	All types (KABCO)	**0.83**	**0.03**
	All types (KABC)	**0.80**	**0.04**
	Bike-related (KABCO)	**0.44**	**0.08**
	Bike-related (KABC)	**0.40**	**0.09**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-39: CMFs for *Adding a Bike Lane* based on Different AADT per Lane (from CMFunction)

Setting (Road Type)	Crash Type (Severity)	AADT per Lane (veh/day)					
		2500	5000	7500	10000	12500	15000
		CMF					
Urban (Arterials)	All types (KABC)	0.48	0.68	0.79	0.85	0.91	0.94

Table 10-40: CMFs for *Increasing Shoulder Width* in School Zone Area (from CMFunction)

Setting (Road Type)	Increasing shoulder width	All types crashes			
		KABC		KAB	
		CMF	S.E	CMF	S.E
Urban (School Zone Area)	Base: no changes	1.000	-	1.000	-
	Increasing 2ft	**0.84**	**0.03**	**0.84**	**0.05**
	Increasing 4ft	**0.71**	**0.03**	**0.71**	**0.04**
	Increasing 6ft	**0.59**	**0.02**	**0.60**	**0.03**
	Increasing 8ft	**0.50**	**0.02**	**0.50**	**0.03**
	Increasing 10ft	**0.42**	**0.02**	**0.42**	**0.02**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-41: CMFs for *Installation of Flashing Beacon at School Zone Signs* in School Zone Area

Setting (Road Type)	All types crashes			
	KABC		KAB	
	CMF	S.E	CMF	S.E
Urban (School Zone Area)	**0.72**	**0.15**	**0.64**	**0.18**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-42: CMFs for *Changing School Zone Speed Limits (from '25-35mph' to '15-20mph')* in School Zone Area

Setting (Road Type)	Heavy vehicle related crashes					
	KABCO		KABC		KAB	
	CMF	S.E	CMF	S.E	CMF	S.E
Urban (School Zone Area)	**0.61**	**0.20**	**0.50**	**0.13**	**0.48**	**0.26**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-43: CMFs for *Decreasing Number of Driveways* in School Zone Area (from CMFunction)

Setting (Road Type)	Decreasing number of driveways	Non-motorized (pedestrian+bike) crashes	
		KABCO	
		CMF	S.E
Urban (School Zone Area)	Base: no changes	1.000	-
	1 driveway	**0.82**	**0.10**
	2 driveways	**0.67**	**0.08**
	3 driveways	**0.54**	**0.07**
	4 driveways	**0.44**	**0.05**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-44: CMFs for *Widening Urban 4-Lane to 6-Lane Roadways* based on Different Time Periods

Setting (Road Type)	Crash Type (Severity)	Time Periods	CMF	Std. Error
Urban (Divided 4-lane Roadways)	All types (KABCO)	1st year	0.90	0.07
		2nd year	**0.85**	**0.07**
		3rd year	**0.80**	**0.06**
		4th year	**0.80**	**0.06**
		All years	**0.85**	**0.07**
	All types (KABC)	1st year	**0.84**	**0.09**
		2nd year	**0.76**	**0.09**
		3rd year	**0.70**	**0.08**
		4th year	**0.70**	**0.08**
		All years	**0.76**	**0.09**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-45: CMFs for *Widening Urban 4-Lane to 6-Lane Roadways* based on Different LOS Changes (from CMFunction)

Setting (Road Type)	Crash Type (Severity)	LOS Changes in before and after periods					
		LOS E of 4-lane → LOS C of 6-lane		LOS E of 4-lane → LOS D of 6-lane		LOS D of 4-lane → LOS D of 6-lane	
		CMF	S.E	CMF	S.E	CMF	S.E
Urban (Divided 4-lane Roadways)	All types (KABCO)	0.81**	0.08	0.85*	0.10	0.92	0.09
	All types (KABC)	0.66**	0.12	0.74*	0.15	0.87	0.17

**: significant at a 95% confidence level, *: significant at a 90% confidence level

Table 10-46: CMFs for *Widening Urban 4-Lane to 6-Lane Roadways* based on Different LOS Changes

Setting (Road Type)	Crash Type (Severity)	Shoulder width ≤ 4 ft		Shoulder width ≥ 6 ft	
		CMF	S.E	CMF	S.E
Urban (Divided 4-lane Roadways)	All types (KABCO)	0.92	0.10	0.74**	0.10
	All types (KABC)	0.81*	0.11	0.70**	0.15

**: significant at a 95% confidence level, *: significant at a 90% confidence level

Table 10-47: CMFs for *Increasing Lane Width* (from CMFunction)

Setting (Road Type)	Lane width	All types crashes			
		KABCO	KABC	KAB	KA
		CMF (S.E)			
Urban (All Roadways)	Posted speed limit: 30 mph				
	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
	11 ft	**0.990 (0.004)**	**0.969 (0.001)**	**0.965 (0.001)**	**0.933 (0.001)**
	12 ft	**0.986 (0.005)**	**0.957 (0.001)**	**0.952 (0.001)**	**0.908 (0.001)**
	13 ft	**0.988 (0.004)**	**0.964 (0.001)**	**0.960 (0.001)**	**0.923 (0.001)**
	14 ft	**0.967 (0.004)**	**0.901 (0.001)**	**0.890 (0.001)**	**0.796 (0.001)**
	Posted speed limit: 40 mph				
	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
	11 ft	**0.986 (0.005)**	**0.959 (0.001)**	**0.954 (0.001)**	**0.912 (0.001)**
	12 ft	**0.981 (0.005)**	**0.943 (0.001)**	**0.936 (0.001)**	**0.879 (0.001)**
	13 ft	**0.984 (0.005)**	**0.953 (0.001)**	**0.947 (0.001)**	**0.899 (0.001)**
	14 ft	**0.956 (0.003)**	**0.871 (0.001)**	**0.856 (0.001)**	**0.737 (0.001)**
	Posted speed limit: 50 mph				
	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
	11 ft	**0.983 (0.005)**	**0.949 (0.001)**	**0.943 (0.001)**	**0.891 (0.001)**
	12 ft	**0.976 (0.005)**	**0.929 (0.001)**	**0.921 (0.001)**	**0.851 (0.001)**
	13 ft	**0.981 (0.005)**	**0.941 (0.001)**	**0.934 (0.001)**	**0.876 (0.001)**
	14 ft	**0.945 (0.002)**	**0.841 (0.001)**	**0.823 (0.001)**	**0.683 (0.001)**
	Lane width	Bike related crashes			
		KABCO	KABC	KAB	KA
	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	-
	11 ft	**0.830 (0.072)**	**0.815 (0.074)**	**0.829 (0.084)**	-
	12 ft	**0.770 (0.094)**	**0.751 (0.095)**	**0.768 (0.110)**	-
	13 ft	**0.806 (0.072)**	**0.791 (0.074)**	**0.805 (0.084)**	-
	14 ft	**0.539 (0.156)**	**0.510 (0.154)**	**0.538 (0.184)**	-

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-48: CMFs for *Increasing Bike Lane Width* (from CMFunction)

Setting (Road Type)	Bike lane width	All types crashes		
		KABCO	KABC	KAB
		CMF (S.E)		
Urban (All Roadways)	2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
	3 ft	**0.988 (0.005)**	**0.973 (0.004)**	**0.975 (0.004)**
	4 ft	**0.977 (0.009)**	**0.949 (0.008)**	**0.953 (0.007)**
	5 ft	**0.971 (0.011)**	**0.936 (0.010)**	**0.941 (0.009)**
	6 ft	**0.972 (0.011)**	**0.938 (0.009)**	**0.942 (0.009)**
	7 ft	**0.979 (0.008)**	**0.954 (0.007)**	**0.957 (0.007)**
	Bike lane width	Bike related crashes		
		KABCO	KABC	KAB
	2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)
	3 ft	**0.964 (0.006)**	**0.965 (0.007)**	**0.963 (0.007)**
	4 ft	**0.934 (0.012)**	**0.935 (0.012)**	**0.933 (0.013)**
	5 ft	**0.917 (0.015)**	**0.918 (0.015)**	**0.915 (0.017)**
	6 ft	**0.919 (0.014)**	**0.920 (0.015)**	**0.917 (0.016)**
	7 ft	**0.940 (0.011)**	**0.940 (0.011)**	**0.938 (0.012)**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-49: CMFs for *Increasing Median Width* (from CMFunction)

Setting (Road Type)	Median width	All types crashes			
		KABCO	KABC	KAB	KA
		CMF (S.E)			
Urban (All Roadways)	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
	20 ft	**0.953 (0.015)**	**0.950 (0.014)**	**0.947 (0.014)**	**0.938 (0.017)**
	30 ft	**0.908 (0.029)**	**0.903 (0.027)**	**0.898 (0.027)**	**0.880 (0.032)**
	40 ft	**0.866 (0.042)**	**0.858 (0.039)**	**0.850 (0.038)**	**0.825 (0.045)**
	50 ft	**0.825 (0.053)**	**0.815 (0.049)**	**0.806 (0.048)**	**0.774 (0.056)**
	Median width	Bike related crashes			
		KABCO	KABC	KAB	KA
	10 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	-
	20 ft	**0.867 (0.025)**	**0.877 (0.026)**	**0.881 (0.030)**	-
	30 ft	**0.751 (0.032)**	**0.770 (0.046)**	**0.776 (0.053)**	-
	40 ft	**0.651 (0.045)**	**0.675 (0.061)**	**0.683 (0.070)**	-
	50 ft	**0.564 (0.056)**	**0.592 (0.071)**	**0.602 (0.082)**	-

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-50: CMFs for *Increasing Shoulder Width* (from CMFunction)

Setting (Road Type)	Shoulder width	All types crashes			
		KABCO	KABC	KAB	KA
		CMF (S.E)			
Urban (All Roadways)	2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	1.000 (-)
	4 ft	**0.924 (0.013)**	**0.933 (0.013)**	**0.941 (0.013)**	**0.937 (0.016)**
	6 ft	**0.854 (0.024)**	**0.870 (0.023)**	**0.886 (0.024)**	**0.878 (0.030)**
	8 ft	**0.789 (0.034)**	**0.812 (0.033)**	**0.834 (0.034)**	**0.823 (0.042)**
	10 ft	**0.730 (0.041)**	**0.758 (0.041)**	**0.785 (0.042)**	**0.772 (0.052)**
	12 ft	**0.674 (0.048)**	**0.707 (0.047)**	**0.739 (0.050)**	**0.723 (0.061)**
	Shoulder width	Bike related crashes			
		KABCO	KABC	KAB	KA
	2 ft (Base)	1.000 (-)	1.000 (-)	1.000 (-)	-
	4 ft	**0.874 (0.023)**	**0.873 (0.024)**	**0.884 (0.027)**	-
	6 ft	**0.764 (0.039)**	**0.762 (0.041)**	**0.781 (0.048)**	-
	8 ft	**0.668 (0.052)**	**0.665 (0.054)**	**0.690 (0.064)**	-
	10 ft	**0.584 (0.060)**	**0.580 (0.063)**	**0.610 (0.076)**	-
	12 ft	**0.510 (0.066)**	**0.506 (0.069)**	**0.539 (0.084)**	-

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-51: CMFs for *Resurfacing*

Setting (Road Type)	Crash type (Severity)	CMF	SE
Urban (All Roadways)	All (KABCO)	**0.93***	0.04
	All (KABC)	**0.89****	0.05
	All (KAB)	**0.86****	0.06

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-52: CMFs for *Resurfacing* based on Different Time Periods

Setting (Road Type)	Crash type (Severity)	CMFs (S.E)			
		1st year after treated	2nd year after treated	3rd year after treated	4th year after treated
Urban (All Roadways)	All (KABCO)	0.77** (0.07)	0.85** (0.07)	1.02 (0.08)	1.15 (0.09)
	All (KABC)	0.69** (0.09)	0.79** (0.10)	0.92 (0.11)	1.15 (0.13)

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-53: CMFs for *Resurfacing* based on Different Heavy Vehicle Volume Rates

Setting (Road Type)	Crash type (Severity)	Heave vehicle volume rate ≤ 3.3%		Heave vehicle volume rate > 3.3%	
		CMF	SE	CMF	SE
Urban (All Roadways)	All (KABCO)	0.94	0.04	0.90**	0.05

**: Significant at a 95% confidence interval

10.1.5 Freeways

Table 10-54: CMFs for *Adding Rumble Strips*

Setting (Road Type)	Crash type (Severity)	CMF	SE
Urban/Rural (Freeways)	All (KABCO)	**0.77**	**0.03**
	All (KABC)	**0.81**	**0.03**
	All (KAB)	**0.87**	**0.03**
	All (KA)	**0.92**	**0.05**
	ROR (KABCO)	**0.83**	**0.04**
	ROR (KABC)	**0.87**	**0.04**
	ROR (KAB)	**0.88**	**0.04**

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-55: CMFs for *Adding Lanes by Narrowing Existing Lane and Shoulder Widths*

Setting (Road Type)	Crash type (Severity)	CMF	SE
Urban/Rural (Freeways)	All (KABCO)	**1.11**	**0.05**
	All (KABC)	**1.57**	**0.22**
	All (KAB)	1.22	0.18
	All (KA)	1.26	0.20

Note: The CMFs in bold are statistically significant at a 95% confidence level.

Table 10-56: CMFs for *Installation of Roadside Barriers*

Setting (Road Type)	Crash type (Severity)	Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
		CMF	SE	CMF	SE
Urban/Rural (Freeways)	All (KABCO)	1.04	0.03	1.09**	0.03
	All (KABC)	0.96	0.04	1.01	0.04
	All (KAB)	0.82**	0.05	0.85**	0.05
	ROR (KABCO)	0.95	0.05	1.01	0.05
	ROR (KABC)	0.84**	0.06	0.88*	0.06
	ROR (KAB)	0.74**	0.07	0.75**	0.08

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-57: CMFs for *Installation of Roadside Barriers* based on Different Vehicle Types

Setting (Road Type)	Different vehicle types	Crash type (Severity)	Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
			CMF	SE	CMF	SE
Urban/Rural (Freeways)	Passenger vehicle crashes	ROR (KABCO)	1.03	0.08	1.15*	0.08
		ROR (KABC)	0.92	0.08	0.98	0.09
		ROR (KAB)	0.81*	0.10	0.81*	0.11
	Heavy vehicle crashes	ROR (KABCO)	0.90	0.08	0.93	0.09
		ROR (KABC)	0.72**	0.10	0.75**	0.11
		ROR (KAB)	0.66**	0.12	0.65**	0.13

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-58: CMFs for *Installation of Roadside Barriers* based on Different Ranges of Driver Age

Setting (Road Type)	Different driver age	Crash type (Severity)	Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
			CMF	SE	CMF	SE
Urban/Rural (Freeways)	Young age driver (15~24 years old) crashes	ROR (KABCO)	1.06	0.10	1.12	0.11
		ROR (KABC)	1.06	0.14	1.11	0.15
		ROR (KAB)	0.91	0.16	0.95	0.18
	Middle age driver (25~64 years old) crashes	ROR (KABCO)	0.93	0.06	1.05	0.08
		ROR (KABC)	0.79**	0.07	0.85*	0.08
		ROR (KAB)	0.69**	0.09	0.70**	0.10
	Old age driver (more than 64 years old) crashes	ROR (KABCO)	0.91	0.15	0.93	0.17
		ROR (KABC)	0.80	0.23	0.80	0.25
		ROR (KAB)	0.62	0.25	0.58*	0.25

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-59: CMFs for *Installation of Roadside Barriers* based on Different Weather Conditions

Setting (Road Type)	Different weather conditions	Crash type (Severity)	Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
			CMF	SE	CMF	SE
Urban/Rural (Freeways)	Normal weather	ROR (KABCO)	0.92	0.06	0.95	0.72
		ROR (KABC)	0.82**	0.08	0.87	0.09
		ROR (KAB)	0.76**	0.10	0.79*	0.11
	Rain and wet surface condition	ROR (KABCO)	0.92	0.08	1.12	0.09
		ROR (KABC)	0.90	0.10	0.96	0.11
		ROR (KAB)	0.75**	0.12	0.75*	0.13

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-60: CMFs for *Installation of Roadside Barriers* based on Different Time

Setting (Road Type)	Different time	Crash type (Severity)	Roadside Barriers (W-Beam + Concrete)		W-Beam Guardrail Only	
			CMF	SE	CMF	SE
Urban/Rural (Freeways)	Day time	ROR (KABCO)	0.96	0.06	1.05	0.07
		ROR (KABC)	0.94	0.08	1.01	0.09
		ROR (KAB)	0.84*	0.10	0.89	0.12
	Night time	ROR (KABCO)	0.92	0.09	0.98	0.10
		ROR (KABC)	0.71**	0.09	0.73**	0.10
		ROR (KAB)	0.60**	0.11	0.53**	0.11

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-61: CMFs for *Changing Shoulder Width* (from CMFunction)

Setting (Road Type)	Changes of shoulder width	All Crashes	ROR Crashes	
		KAB	KABC	KAB
		CMF (S.E)		
Urban/Rural (Freeways)	6 ft	1.15 (0.11)	1.27* (0.15)	1.25 (0.16)
	10 ft (Base)	1.00	1.00	1.00
	14 ft	0.86* (0.08)	0.79** (0.09)	0.80* (0.11)

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

Table 10-62: CMFs for *Installation of Roadside Barriers + Changing Shoulder Width* (from CMFunction)

Setting (Road Type)	Changes of shoulder width	All Crashes	ROR Crashes	
		KAB	KABC	KAB
			CMF (S.E)	
Urban/Rural (Freeways)	6 ft	1.25* (0.15)	1.49** (0.24)	1.43* (0.26)
	10 ft (Base)	1.00	1.00	1.00
	14 ft	0.80* (0.11)	0.67** (0.11)	0.70** (0.13)

**: Significant at a 95% confidence interval, *: Significant at a 90% confidence interval

10.2 Intersections

Table 10-63: CMFs for *Signalization of Stop-Controlled Intersections*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Rural (3-leg, 4-leg)	All types (KABCO)	**0.56**	**0.03**
	All types (KAB)	**0.75**	**0.14**
	Rear-end (KABCO)	**1.91**	**0.52**
	Angle + Left-turn (KABCO)	**0.66**	**0.11**
Urban (3-leg)	All types (KABCO)	**1.73**	**0.20**
	All types (KABC)	**1.38**	**0.21**
	Rear-end (KABCO)	**2.93**	**0.66**
	Single vehicle (KABCO)	**3.12**	**1.26**
	Multi vehicle (KABCO)	**1.63**	**0.19**
	Day time (KABCO)	**1.55**	**0.21**
	Night time (KABCO)	**2.20**	**0.50**
Urban (4-leg)	All types (KABCO)	**1.17**	**0.05**
	All types (KABC)	**1.33**	**0.08**
	All types (KAB)	**0.79**	**0.06**
	Rear-end (KABCO)	**2.30**	**0.20**
	Angle + Left-turn (KABCO)	**0.59**	**0.04**
	Single vehicle (KABCO)	**1.72**	**0.26**
	Multi vehicle (KABCO)	**1.16**	**0.05**
	Day time (KABCO)	**1.17**	**0.06**
	Night time (KABCO)	**1.59**	**0.15**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-64: CMFs for *Adding Left-Turn Lane*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Rural (3-leg)	All types (KABCO)	**0.56**	**0.07**
	All types (KABC)	**0.73**	**0.17**
Rural (4-leg)	All types (KABCO)	**0.69**	**0.11**
	All types (KABC)	**0.64**	**0.14**

Note: The CMFs in bold are statistically significant at a 85% confidence level.

Table 10-65: CMFs for *Adding Left-Turn Lane on the Minor Road*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Rural (3-leg / 4-leg)	Single vehicle (KABCO)	**0.68**	**0.12**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-66: CMFs for *Adding Red-Light Cameras at Red-Light-Camera-Equipped Intersections*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Urban (3-leg and 4-leg Signal)	Angle (KABCO)	**0.84**	**0.04**
	Angle (KABC)	**0.87**	**0.09**
	Rear-end (KABCO)	**1.17**	**0.07**
	Rear-end (KABC)	**1.23**	**0.09**

Note: The CMFs in bold are statistically significant at a 85% confidence level.

Table 10-67: CMFs for *Adding Red-Light Cameras at Adjacent Non-Red-Light-Camera-Equipped Intersections*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Signal)	Angle (KABCO)	**0.91**	**0.02**
	Angle (KABC)	0.92	0.09
	Rear-end (KABCO)	0.99	0.12
	Rear-end (KABC)	1.08	0.10

Note: The CMFs in bold are statistically significant at a 85% confidence level.

Table 10-68: CMFs for *Adding Red-Light Cameras at Red-Light-Camera-Equipped Intersections* based on Different Ranges of Time Periods

Setting (Intersection Type)	Crash Type (Severity)	Months after Treatment	CMF	Std. Error
Urban (3-leg and 4-leg Signal)	All types (KABCO)	1-36	**0.87**	**0.06**
		1-18	**0.70**	**0.06**
		19-36	1.09	0.09
	All types (KABC)	1-36	**0.65**	**0.06**
		1-18	**0.52**	**0.07**
		19-36	**0.79**	**0.08**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-69: CMFs for *Adding Red-Light Cameras at Red-Light-Camera-Equipped Intersections* based on Different Number of Months (from CMFunction)

Setting (Intersection Type)	Crash Type (Severity)	Number of months after treatment	CMF	Std. Error
Urban (3-leg and 4-leg Signal)	All types (KABCO)	3	0.90	0.22
		6	0.77	
		12	**0.63**	
		18	0.78	
		24	0.82	
		30	**0.64**	
		36	**1.71**	
		42	1.08	
		48	0.97	
	All types (KABC)	3	**0.64**	0.17
		6	**0.66**	
		12	**0.41**	
		18	**0.55**	
		24	0.87	
		30	**0.71**	
		36	**0.68**	
		42	**0.63**	
		48	**0.64**	

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-70: CMFs for *Widening Median Width* (from CMFunction)

Setting (Intersection Type)	Crash Type (Severity)	Median Width	CMF	Std. Error
Rural (Signalized-Major Road)	Single vehicle (KABCO)	0 (base)	1	-
		10	**1.14**	**0.01**
		20	**1.30**	**0.13**
		30	**1.47**	**0.20**
		40	**1.67**	**0.27**
Rural (Signalized-Minor Road)	All types (KABC)	0 (base)	1	-
		2	**0.98**	**0.01**
		4	0.97	0.02
		6	**0.95**	**0.03**
		8	**0.93**	**0.04**
		10	0.92	0.06
	All types (KAB)	0 (base)	1	-
		2	**0.98**	**0.01**
		4	**0.95**	**0.02**
		6	**0.93**	**0.03**
		8	**0.91**	**0.05**
		10	**0.89**	**0.06**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-71: CMFs for *Decreasing Skew Angle based on 0 Degree Base (from CMFunction)*

Setting (Intersection Type)	Skew Angle (Degree)	Crash Type (Severity)	CMF	Std. Error
Rural (Signalized)	10 Degree to 0 Degree	Single (KABCO)	**0.88**	**0.06**
	20 Degree to 0 Degree	Single (KABCO)	**0.78**	**0.12**
	30 Degree to 0 Degree	Single (KABCO)	**0.69**	**0.17**
	40 Degree to 0 Degree	Single (KABCO)	**0.61**	**0.23**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-72: CMFs for *Installing Retroreflective Backplates to Signals*

Setting (Intersection Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Signal)	All (KABCO)	**0.72**	**0.09**
	All (KABC)	**0.74**	**0.10**
	Rear-end (KABCO)	**0.78**	**0.12**
	Day time (KABCO)	**0.71**	**0.10**
	Night time (KABC)	**0.67**	**0.11**

Note: The CMFs in bold are statistically significant at a 90% confidence level.

Table 10-73: CMFs for *Adding Red Light Running Camera Citation Sign*

Setting (Intersection Type)	AADT range	Crash Type (Severity)	CMF	Std. Error
Urban / Rural (Signal)	AADT > 50000	All (KABCO)	**0.74**	**0.12**
		All (KABC)	**0.78**	**0.12**
		All (KAB)	0.79	0.13
	AADT < 50000	All (KABCO)	1.23	0.2
		All (KAB)	1.25	0.21

Note: The CMFs in bold are statistically significant at a 90% confidence level.

10.3 Special Facilities

Table 10-74: CMFs for *Converting Traditional Mainline Toll Plaza to Hybrid Mainline Toll Plaza*

Setting (Road Type)	Crash Type (Severity)	CMF	Std. Error
Urban (Freeways)	All types (KABCO)	**0.53**	**0.05**
	All types (KABC)	**0.54**	**0.07**
	All types (O)	**0.46**	**0.06**
	Rear-end (KABCO)	**0.34**	**0.06**
	Lane-change-related* (KABCO)	**0.45**	**0.09**

Note: The CMFs in bold are statistically significant at a 95% confidence level.
*Lane-change-related crashes include sideswipe, lost control, overturned and angle crashes.

Table 10-75: CMFs for *Converting Traditional and Hybrid Mainline Toll Plaza (TMTP and HMTP) to All Electronic Toll Collection (AETC)*

Setting (Road Type)	Crash Type (Severity)	TMTP to AETC		HMTP to AETC	
		CMF	Std. Error	CMF	Std. Error
Urban (Freeways)	All types (KABCO)	**0.24**	**0.06**	**0.76**	**0.08**
	All types (KABC)	**0.25**	**0.08**	**0.72**	**0.06**
	All types (O)	**0.32**	**0.07**	**0.80**	**0.10**
	Rear-end (KABCO)	**0.20**	**0.09**	**0.78**	**0.09**
	Lane-change-related* (KABCO)	**0.26**	**0.04**	**0.78**	**0.07**

Note: The CMFs in bold are statistically significant at a 95% confidence level.
*Lane-change-related crashes include sideswipe, lost control, overturned and angle crashes.

Table 10-76: CMFs for *Converting High-Occupancy Vehicle (HOV) Lanes to High-Occupancy Toll (HOT) Lanes*

Setting (Road Type)	Crash Type (Severity)	HOV to HOT lanes	
		CMF	Std. Error
Urban (Freeways)	All types (KABCO)	**0.80**	**0.10**
	All types (KABC)	**0.72**	**0.12**
	All types (O)	**0.63**	**0.11**
	Lane-change-related* (KABCO)	**0.61**	**0.10**
	Rear-end (KABCO)	**0.62**	**0.07**
	All others (KABCO)	**0.77**	**0.13**

Note: The CMFs in bold are statistically significant at a 90% confidence level.
*Lane-change-related crashes include sideswipe, lost control, overturned and angle crashes.

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APPENDIX A

Survey of Roadways Improvements

Dear Colleague,
This survey has been prepared by the University of Central Florida as part of a FDOT project to validate the Highway Safety Manual's Crash Modification Factors based on the conditions relevant to the State of Florida. Please enable Word Macro Content before you start. If you face problems filling out this form electronically, you can print it out and fill it out manually. Once finished, please scan it and email it to the email address specified at the end of this survey. Your kind assistance will help in providing safer roadways in Florida. Once we complete the final report, respondents can review the results at the FDOT website http://www.dot.state.fl.us/research-center/.

County/District Name: Click here to enter text.
Name of Respondent: Click here to enter text.
Email: Click here to enter text.
Phone: Click here to enter text.

1. Please click the box(s) below for common intersection treatments in your county/district. (check all that apply)

☐ Provide a right-turn lane on one or more approaches to an intersection
☐ Provide a channelized right-turn lane at intersections
☐ Provide a left-turn lane on one or more approaches to three-leg intersections
☐ Provide a left-turn lane on one or more approaches to four-leg Intersections
☐ Provide a channelized left-turn lane at four-leg intersections
☐ Provide a channelized left-turn lane at three-leg intersections
☐ Add 'No Turn on Red' sign at intersections
☐ Install red-light running-camera at intersections
☐ Add street light at intersection
☐ Install physical barrier at turn lane
☐ Remove barrier in the clear vision area in sight triangle (Improve sight distance)
☐ Convert four-leg intersection to two three-leg intersections
☐ Remove unwarranted signals on one-way streets
☐ Convert signal control intersection to modern roundabout

☐ Convert a stop control intersection to modern roundabout
☐ Convert 2-way stop control intersection to 4-way stop control intersection
☐ Convert 4-way stop control intersection to 2-way stop control intersection
☐ Convert 2-way stop control intersection to signal control intersection
☐ Convert 4-way stop control intersection to signal control intersection
☐ Increase intersection median width
☐ Prohibit left-turns and/or U-turns by installing 'No Left Turn' and 'No U-Turn' signs
☐ Provide "Stop Ahead" pavement markings
☐ Provide flashing beacons at stop-controlled intersections
☐ Modify left-turn phase
☐ Replace direct left-turns with right-turns/U-turns combination
☐ Permit right-turn-on-red operation
☐ Modify change plus clearance interval
☐ Provide bicycle lanes or wide curb lanes at intersections
☐ Narrow roadway at pedestrian crossing
☐ Install raised pedestrian crosswalk
☐ Install raised bicycle crossing
☐ Mark crosswalks at uncontrolled locations, intersection or midblock
☐ Provide a raised median or refuge island at marked and unmarked crosswalks
☐ Install pedestrian signal heads at signalized intersections
☐ Install pedestrian countdown signals
☐ Install automated pedestrian detectors
☐ Install stop lines and other crosswalk enhancements
☐ Provide exclusive pedestrian signal timing pattern
☐ Provide leading pedestrian interval signal timing pattern
☐ Provide actuated control
☐ Operate signals in 'Night-Flash' mode
☐ Install additional pedestrian signs
☐ Install rumble strips on intersection approaches
☐ Install white light
☐ Install left turn flashing yellow arrow signals at signalized intersections
☐ Install reflectorized signal plates at signalized intersections

2. If not addressed in question 1, what are other common *safety treatments* for intersections in your county/district?

Click here to enter text.

3. If not addressed in question 1, what are other common *operational treatments* for intersections in your county/district?

Click here to enter text.

4. **Please left click the box below for common roadway segment treatments in your county/district. (check all that apply)**

- ☐ Add shoulder rumble strips on rural highways
- ☐ Add shoulder rumble strips on freeways
- ☐ Widen shoulder width on rural highways
- ☐ Widen shoulder width on freeways
- ☐ Add shoulder rumble strips + Widening shoulder width
- ☐ Convert two-way left-turn lanes (TWLTL) to raised medians
- ☐ Add street light
- ☐ Modify (increase or decrease) median width
- ☐ Add raised median
- ☐ Convert 4-lane undivided urban roadways to 3-lane roadways including TWLTL
- ☐ Add bike lanes
- ☐ Change speed limits in school zones
- ☐ Add guardrails on roadside
- ☐ Modify (increase or decrease) lane width
- ☐ Change type of median barrier (cable, concrete, steel, trees)
- ☐ Change type of shoulder guardrails (cable, concrete, W-beam)
- ☐ Change type of shoulder (paved, turf, gravel)
- ☐ Remove roadside fixed objects
- ☐ Increase distance to roadside features
- ☐ Decrease number of utility poles
- ☐ Add through lanes (Conversion of 2-lane to 4-lane, 4-lane to 6-lane)
- ☐ Add curb and sidewalks to shoulder
- ☐ Resurface roadways
- ☐ Change parking type (parallel, angle)
- ☐ Prohibit on-street parking
- ☐ Implement time-limited parking restrictions
- ☐ Decrease number of driveways

5. **If not addressed in question 4, what are other common *safety treatments* for roadway segments in your county/district?**

Click here to enter text.

6. **If not addressed in question 4, what are other common *operational treatments* for roadway segments in your county/district?**

Click here to enter text.

Thank you for filling out the survey. Your help will provide us valuable information to improve the traffic safety in Florida. Lastly, please ***provide countermeasures/improvements/geometric changes that have been implemented in your county/district with locations and date of construction if available.*** This data will only be used for research purposes by UCF and FDOT and will not be accessible to others unless authorized. Your help is greatly appreciated. Please email ***this survey*** along with ***data of countermeasures with location and installation data*** if available to **jwang@knights.ucf.edu**

For your convenience, you can use the submit button if you have Office Outlook. If the submit button does not work properly, you can use an email source other than Outlook. Please put "Survey HSM Part D Submit – County/District Name" as the title. If you have any questions, concerns or suggestions, please feel free to contact us through email. We really appreciate your help.

Mohamed Abdel-Aty, PhD, PE
Professor and Chair