Final Report

Operational and Safety Impacts of Restriping Inside Lanes of Urban Multilane Curbed Roadways to 11 Feet or Less to Create Wider Outside Curb Lanes for Bicyclists

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Report Prepared for:

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SI* (MODERN METRIC) CONVERSION FACTORS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
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				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	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
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
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				
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
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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16. Abstract

This study analyzes the influence of several site characteristics on the operational behavior of motorists when passing bicyclists on wider outside through lanes. More than 2000 videotaped passing events were analyzed. Several measures of effectiveness were used in this analysis, including: lateral separation between the motor vehicle and bicyclist; motor vehicle shift to the inside lane; motor vehicle outside through lane usage; and motor vehicle speeds before, during and after passing bicyclists. Regression analysis was used to examine the lateral separation between the motor vehicle and bicyclist, vehicle lateral shift to the inside lane, and motor vehicle outside through lane usage. Motor vehicle speeds were analyzed using a paired-*t* test. The results show that motorists pass closer to bicyclists when a bicyclist is a male, the outside through lane is narrower, motor vehicles are in the adjacent inside lanes, and the overtaking motor vehicle is smaller. The study findings suggest the frequency and percentage of movement into the adjacent inside lane by overtaking drivers increases with a decrease in the width of the outside through lane. Lateral movement into the inside lanes was also found to increase when the bicyclist was female and when volume of traffic increased. Compact cars had less lateral shift than other vehicle types. The results further show that there is a tendency of motorists to move from the outside through lane to inside lane after recognizing that there is a bicyclist downstream. Generally, drivers reduced speeds when passing bicyclists and then accelerated after passing bicyclists.

This study also developed crash modification factors (CMFs) for asymmetric curb and gutter four-lane roadways with a flush, two-way left-turn lane (TWLTL) and raised median. The results show that given a 24-ft total lane width for inside and outside through lanes, restriping the outside through lane to provide 13 ft and leaving the inside lane with 11 ft would result in a slight reduction of crashes for four-lane sections with raised median. The results further show that if an extra half a foot is added to the outside asymmetric lane to make it 13.5 ft, while keeping the inside lane width at 11 ft, a decrease in crashes is found for both four-lane sections with raised median and four-lane with TWLTL median.

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EXECUTIVE SUMMARY

The objective of this study was to evaluate whether any significant safety and/or operational benefits are realized in using asymmetrical lane width configurations on multilane roadways with a wider outside lane than inside lane. Operation analysis involved investigation of interactions between motor vehicles and bicyclists using video collected at selected sites across the state. Safety analysis employed crash data archived by the Florida Department of Transportation (FDOT) in developing crash modification factors for asymmetric cross-sections. The following sections present a summary of the findings.

Operational Analysis

The operational analysis involved investigation of the influence of several site characteristics on the operational behavior of motorists when passing bicyclists on asymmetric curb-and-gutter roadways. More than 2000 videotaped passing events at 12 different sites were analyzed. Data was collected during peak hours, for a duration of one to two hours for each site. The riders took advantage of traffic signals to allow motor vehicles to accumulate during a red phase so as to have enough interaction for each cycle and also to manage speeds. Several measures of effectiveness were used in this analysis, including: lateral separation between the motor vehicle and bicyclist; motor vehicle shift to the outside through lane; motor vehicle outside through lane usage; and motor vehicle speeds before, during and after passing bicyclists. Riding was done only during daylight.

The research team collected data on curb-and-gutter asymmetric four- to six-lane roadways with posted speeds ranging from 30 to 45 miles per hour. The outside lane width ranged from 12.5 to 16 ft while the inside lane range was from 10.8 to 12 ft. Although the initial intention was to collect data from asymmetric roadways with lane widths ranging from 13 to 14 ft, segments with outside through lane width wider than 14 ft were included in order to expand the range of analysis.

Regression analysis was used to examine the lateral separation between the motor vehicle and bicyclist, motor vehicle lateral shift to the inside lane, and driver lane choice. Motor vehicle speeds were analyzed using a paired-*t* test. The results from descriptive statistics, 95% confidence intervals, and regression modeling, all point out that lateral separation between motor vehicles and bicyclists is highly influenced by the width of the outside through lane.

The standard lane width is 12 ft. A typical width for a wide outside through lane is 14 ft. Under Florida law, a minimum of 3 ft separation is required between an overtaking motorist and a bicyclist. At lane width of less than 13.5 ft, drivers need to move into the inside lane, at least partially, in order to provide the required minimum clearance of 3 ft.

Other general findings are summarized below:

Lateral Clearance Findings

- The greatest lateral separation (averaging 5.5 ft) was obtained when bicyclists rode between three and four feet from the face of curb.

- An increase in the width of the outside through lane resulted in greater lateral separation between motor vehicles and bicyclists.
- As the volume of motor vehicles increased, lateral separation decreased.
- Motorists provided less separation to bicyclists when other vehicles were present in the inside lane.
- Motorists provided 0.5 ft additional lateral separation to female bicyclists and 0.35 ft additional separation to casually dressed compared to athletically dressed cyclists.

Lateral Shift Findings

- The amount of the motor vehicle body partially shifting into the inside lane was reduced with the increase in the width of the outside through lane.
-
- Passenger cars were observed to have the lowest amount of lateral shift when passing a bicyclist.
- Large trucks were observed to provide the greatest amount of lateral shift when passing, often slowing down and completely moving to the inside lane to allow sufficient lateral separation to bicyclists.
- Less lateral shift was observed with increased vehicular traffic volume.
  The tendency was for drivers to move left if they had the opportunity.

Motor Vehicle Lane Usage Findings

- Given acceptable gaps, there was a tendency of motorists to move from the outside through lane to the inside lane after recognizing that there was a bicyclist downstream.
- In the absence of a bicyclist, more vehicles (56.2% for 4-lane segments, 30.6% for 6-lane segments)) were observed to use the outside through lane.
- In the presence of a bicyclist, a considerable proportion of motor vehicles shifted to the inside lane before passing the bicyclist to avoid sharing the outside through lane with a bicyclist. Only 40.2% of vehicles used the outside through lane when a bicyclist was present for 4-lane segments; 25.7% for 6-lane segments.

Motor vehicle Speed Finding

- On average, drivers reduced their speeds (from 34.13 to 32.76 mph) when passing bicyclists to ensure safe passing maneuver and accelerated (from 32.76 to 36.86) after passing bicyclists.

Safety Analysis

This study developed lane width crash modification factors (CMFs) for asymmetric curb-and-gutter multilane roadways. The roadway segments used were curb-and-gutter four-lane with a raised median (4D) or flush two-way left-turn lane (5T). In total, the analysis reported in this study used 25 centerline miles of 5T segments and 39 centerline miles of 4D roadways.

Development of CMFs followed a protocol described by the Highway Safety Manual (2010). The cross-sectional method was used. Negative binomial regression models were used to model the relationship between crash frequency and model variables. Variables considered in modeling included driveway density, median opening density, posted speed limit, inside lane width, outside through lane width, median width, segment length, and average daily traffic (ADT). Six years (2004–2009) of segment crashes were examined. Three crash categories were evaluated;

KABCO { Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), possible injury (C) and property damage only crashes (O)}, KABC {Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), and possible injury crashes (C)}, and PDO (property damage only) crashes.

The results of the safety analysis are summarized in Exhibit 1. A CMF of 1.00 indicates no influence in causing crashes while CMFs of smaller and greater than 1.00 indicate that a change of a variable from a base value causes a decrease and increase in crashes, respectively. According to the results, crashes decrease as the outside through lane width is increased from 12 ft. This decrease is seen on all types of crashes analyzed in this study, i.e., KABCO, KABC, and PDO crashes. According to the results depicted in Exhibit 1, for 4D segments, the effect of inside lane width is insignificant, indicating that the decrease of lane width from 12 ft to 11 ft does not cause an increase in crash frequency.

Exhibit 1 Comparison of CMFs for 4D and 5T When Inside Lane Width is Fixed to 11 ft While Outside Through Lane Width Varies

	Base Line Condition	[4D CMF] (5T CMF) Ratio (5T CMF)/(4D CMF)					
Outside Lane Width Range (ft)	11.8-12.2	11.8-12.2	12.3-12.7	12.8-13.2	13.3-13.7	13.8-14.2	14.3-14.7
Outside Lane Width (ft)	12	12	12.5	13	13.5	14	14.5
Inside Lane Width Range (ft)	11.8-12.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2
Inside Lane Width (ft)	12	11	11	11	11	11	11
CMF for KABCO Crashes	[1.00] (1.00) 1.00	[1.00] (1.88) 1.88	[0.84] (1.40) 1.67	[0.70] (1.04) 1.49	[0.58] (0.77) 1.32	[0.49] (0.58) 1.18	[0.41] (0.43) 1.05
CMF for KABC Crashes	[1.00] (1.00) 1.00	[1.00] (2.12) 2.12	[0.86] (1.65) 1.92	[0.73] (1.28) 1.75	[0.63] (1.00) 1.59	[0.54] (0.78) 1.44	[0.64] (0.61) 0.95
CMF for PDO Crashes	[1.00] (1.00) 1.00	[1.00] (1.00) 1.00	[0.83] (0.81) 0.98	[0.69] (0.66) 0.96	[0.57] (0.54) 0.95	[0.48] (0.44) 0.92	[0.40] (0.36) 0.9

For 5T sections, the results show an increase in crashes as the inside lane width is reduced to 11 ft while the outside through lane width is increased to 12.5 ft. This trend was observed for both KABCO and KABC crashes, but not for PDO crashes. CMFs for PDO crashes were found to be independent of the inside lane width, but dependent of outside through lane width. Relative to outside through lane width of 12 ft, the CMFs for PDO crashes were found to decrease as the outside through lane width increased.

As stated above, for 4D segments, narrowing the inside lane from 12 ft to 11 ft did not result in an increase in crash frequency for any of the three types of crashes. Also, for 5T segments, the decrease in inside lane width was not significant for PDO crashes. It was only significant for KABCO and KABC crashes, hence higher CMF values for KABCO and KABC crashes for 5T. As far as 5T segments are concerned, higher CMF values for KABCO and KABC crashes might have been attributed to the type of median and might have less to do with the inside lane width. Having higher values of CMFs for KABCO and KABC crashes on roads with a TWLTL is consistent with studies by Mauga and Kaseko (2010) and 15 studies reviewed by Gluck *et al*. (1999). These studies reported crash reduction that range from 3% and 57% for KABCO crashes on roads with raised median in comparison to segments with TWLTL. Mauga and Kaseko (2010) also found a decrease of 21% on KABC crashes for roads with raised median in comparison to those with TWLTL.

Exhibit 1 also shows the ratio between the CMFs developed for 4D and 5T segments with a fixed inside lane of 11 ft while outside through lane width varied from 12.5 ft to 14.5 ft. The results revealed that with respect to KABCO crashes, the CMF for 5T segments, when the inside lane width is 11 ft and the outside through lane width is 12 ft is 1.88 times that of 4D segments. The ratio decreases as the outside through lane width increases from 12.5 ft to 14.5ft, where the 5T CMF is 1.05 times that of 4D segments. A similar trend was observed for KABC crashes as the ratio decreased from 2.12 to 0.95 as the outside through lane width increased from 12 ft to 14.5 ft while keeping the inside lane width constant at 11 ft. As can be seen in Exhibit, for PDO crashes, the ratio of CMFs for 4D segments to CMFs for 5T segments is smaller than 1.0, indicating that for PDO crashes, a higher crash reduction is expected for 5T segments than for 4D segment when the outside through lane width is widened while keeping the inside lane fixed at 11 ft.

In order to answer the research question, i.e., whether the provision of outside lane widths less than 14 ft offers any safety benefits, one needs to compare typical with asymmetrical lane configurations with the same total pavement width. When comparing a typical 12 ft inside and a 12 ft outside through lane width segment (a total of 24 ft) with an asymmetric segment of an 11 ft inside lane and a 13 ft outside through lane, the results in Exhibit1 show that a 4D asymmetric lane configuration would result in fewer crashes (See highlighted cells - CMFs of 0.70, 0.73, and 0.69 for KABCO, KABC, and PDO crashes, respectively). For 4D configurations, given a total of 24 ft pavement width for both lanes, the results presented in Exhibit 1 indicate that restriping a roadway 12 ft to an 11 ft inside and a 13 ft outside through lane would result in a decrease in crashes. For 5T sections, the results are mixed, showing a slight increase for KABCO and KABC crashes (CMFs of 1.04 and 1.28, respectively) and a reduction of PDO crashes (CMF of 0.66), when a typical roadway is retrofitted to an 11 ft inside and a 13 ft outside through lane, respectively. The results also show that as the width of outside lane increases, for both 4D and 5T configurations, crashes decrease.

Report Organization

This report is divided into two major parts – Part A and Part B. Part A covers documentation of how the operational analysis was conducted, providing details on literature search, site selection, data collection, analysis of data, summary of findings, and recommendations for future research, each in a different chapter. Part B presents the safety analysis portion of this study. It is divided into five chapters. The first chapter is introduction. The next chapter provides a summary of the literature on the crash modification factors and safety performance functions. It is followed by a data collection chapter, which outlines the methodology used to gather modeling data. The data collection chapter is followed by the data analysis chapter where the findings are discussed. The final chapter of Part B presents the conclusions and recommendations for further study pertaining to safety analysis.

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LIST OF ACRONYMS AND ABBREVIATIONS

FDOT	Florida Department of Transportation
MPO	Metropolitan planning organization
CMF	Crash modification function or factor
SPF	Safety performance function
TWLTL	Two-way left-turn lane
ADT	Average daily traffic
AADT	Average annual daily traffic
WCL	Wide curb lanes
BL	Bike lane
FHWA	Federal Highway Administration
SUVs	Sports utility vehicles
LOS	Level of service
PDO	Property damaged only
KABC	Fatal (K), incapacitating (A), non-incapacitating (B), and possible injury (C) crashes
KABCO	Fatal (K), incapacitating (A), non-incapacitating (B), possible injury (C) and PDO (O) crashes
8U	Eight-lane road with undivided median
8D	Eight-lane road with divided median
7T	Six-lane road with TWLTL median
6U	Six-lane road with undivided median
6D	Six-lane road with divided median
5T	Four-lane road with TWLTL median
4U	Four-lane road with undivided median
4D	Four-lane road with divided median
3T	Two-lane road with TWLTL median
CAR	Crash analysis report
RCI	Roadway Characteristics Inventory
NB	Negative binomial
EB	Empirical Bayes

PART A: OPERATIONAL ANALYSIS

CHAPTER 1. INTRODUCTION

Across the United States, a great deal of attention is being directed to promoting energy efficient and environmentally friendly modes of transportation. Bicycling forms an integral part of a sustainable transportation system; it provides one of the most energy efficient, cost effective, and environmentally friendly methods of transportation. The growing use of bicycles for commuting and leisure activities is creating conflicts with motorized traffic, mainly because roadway facilities are primarily designed to accommodate motorized traffic alone. In most cases, bicycle lanes (BLs) are the preferred bicycle facility. However, bicycle lanes are the ideal bicycle riding design provision. Historically, 14 ft wide outside through lanes have been implemented to simultaneously accommodate motor vehicles and bicycles in lieu of bike lanes.

In the urban environments where curbs and sidewalks are in place, restriping to widen the outside through lane for the shared use by bicyclists and vehicular traffic is now common. Restriping may result in asymmetrical travel lane, with a narrow inside lane and a wide outside through lane. This report presents the results of the field study conducted to evaluate the interaction between motor vehicles and bicyclists on asymmetrical lane width configuration (curb and gutter roads). Inside lane widths were 10 feet 8 inches to 12 feet and outside through lane ranged from 12 to 16 ft.

The rest of Part A of this report is arranged as follows. The next section presents a summary of literature review followed by the chapter that discusses site selection. It is followed by data collection, data reduction, data analysis and presentation of summary of findings. The report ends by giving recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

Literature search revealed that Harkey *et al.* (1996) had conducted a study to evaluate the impact of WCLs, BLs, and paved shoulders on the interaction between motor vehicles and bicycles. The study evaluated four measures of effectiveness that were considered to be critical to the safety and comfort of bicyclists: (1) lateral placement of bicyclists, (2) lateral placement of the motor vehicles, (3) separation distance between the bicycle and the motor vehicle, and (4) lateral shift by the motorist into an adjacent inside lane when passing a bicyclist. The study found that, on average, the lateral separation between motor vehicles and bicyclists was 5.9 ft and 6.4 ft for BLs and WCLs, respectively. The average position of bicyclists from the edge of the roadway was found to be 1.4 ft for wider outside through lane facilities and 2.6 ft for bicycle lane facilities. However, the study did not investigate the influence of different widths of wider outside through lanes on the above measures of effectiveness.

The Federal Highway Administration (FHWA) has also studied the influence of WCLs. A 1999 study conducted by Hunter *et al*. (1999) and sponsored by FHWA determined that bicycles tended to be positioned about 0.86 ft closer to the curb when passed by a motor vehicle. The data used in this study came from three states – California, Texas, and Florida. The study divided WCLs into two categories – 14 ft wide or less and wider than 14 ft. Another study by Hunter *et al.* (2005) examined the operational effects of retrofitting a 14 ft wide curb lane to an 11 ft wide travel lane with a 3 ft wide bike lane at various locations in Broward County, Florida. The study utilized the staff of the Sheriff's Department and members of a bicycle club as riders in the field study. The study found that the lateral spacing of bicyclists from the curb with striping was greater than that from the curb without striping. The results also showed that the lateral spacing of motor vehicles from the curb was greater with the stripe than without the stripe. On average, motor vehicles were driven 0.5 to 1 ft farther away from the curb where the stripe was newly added. Field observations also revealed that the addition of the stripe effectively reduced the amount of motor vehicle lateral shift to the adjacent lane on these multilane roadways. On average, the lateral shifts were reduced by approximately 15% to 40% at sites where a stripe was newly added. Recent research conducted in the United Kingdom observed that the separation between motor vehicles and bicycles was wider where there were no bike lanes compared to sites that had bike lanes (Parkin and Meyers, 2010).

Another recent study conducted by Hallett *et al.* (2006), and sponsored by the Texas Department of Transportation, reviewed the effectiveness of retrofitting existing roadways to accommodate wide outside lanes. Unlike the previous two studies cited above, this study treated the WCLs and inside lanes as continuous variables. The lane widths ranged between 13.7 ft to 19.5 ft and 9.3 ft to 14.6 ft for WCLs and inside lanes, respectively. The results indicated a significant influence of lane width on lateral position of motorists and lateral shift. Wider outside through lanes were associated with greater values of lateral position of motorists (the distance between the face of curb and motorist's front wheel on the passenger side) and lower rates of motorist's lateral shift to the adjacent lane, compared to narrower outside through lanes.

A summary of literature reviewed so far has revealed the following gaps in the knowledge of operational and safety characteristics of roadways with and without wider outside through lanes.

- Previous studies were primarily aimed at determining the differences in operational characteristics between wider outside through lanes and bike lanes, not the influence of different widths of curb lanes, especially widths ranging between 12 and 14 ft.
- Lateral shifting was considered as a categorical variable with two outcomes, true or false. None of the previous studies examined the extent of lateral shift for each motor vehicle that laterally shifted to the adjacent lane.
- The reported studies did not analyze vehicular speeds at the point where a motor vehicle in the outside through lane is passing a bicyclist.
- Motor vehicle behavior, while traveling in the outside through lane in the presence or absence of bicyclists, has not been investigated by the previous studies.

Consequently, this study is aimed at addressing these knowledge gaps.

CHAPTER 3. SITE SELECTION

Locations for data collection were selected based on the availability of multilane roadway corridors with asymmetric curb and gutter roadways, volunteer bicycle riders, and the availability of vehicular peak traffic. Bicycle and pedestrian coordinators from FDOT districts across the state of Florida were surveyed to provide information on the location of asymmetric curb and gutter roads with lane width greater than 12 ft but narrower than 14 ft. To extend the analysis, the coordinators suggested that asymmetric sections with lane widths wider than 14 ft be included in the study in order to analyze a wider range of lane widths.

It is worth mentioning that while surveying FDOT districts, inconsistencies were discovered in the measurement of lane widths for the outside through lane. For example, the data from Orlando had lane width values measured from the face of curb to the center of the striping dividing the curb and inside lane while most of the other agencies measured the width of the outside through lane as the center-to-center distance between the white stripes. Depending on the method used, dimensions could differ by half a foot to over two feet. FDOT design office officials were contacted to provide guidance on the correct way to measure the width of the outside through lane. According to FDOT design standards, index 600, the width of the outside through lane is measured as the distance from the outside edge of the pavement to the center of the striping that demarcates the outside and inside lanes. Figure 1 illustrates the difference between the above methods of measuring widths of the outside through lanes. In order to be consistent, this study adopted the FDOT standard lane width measurement method.

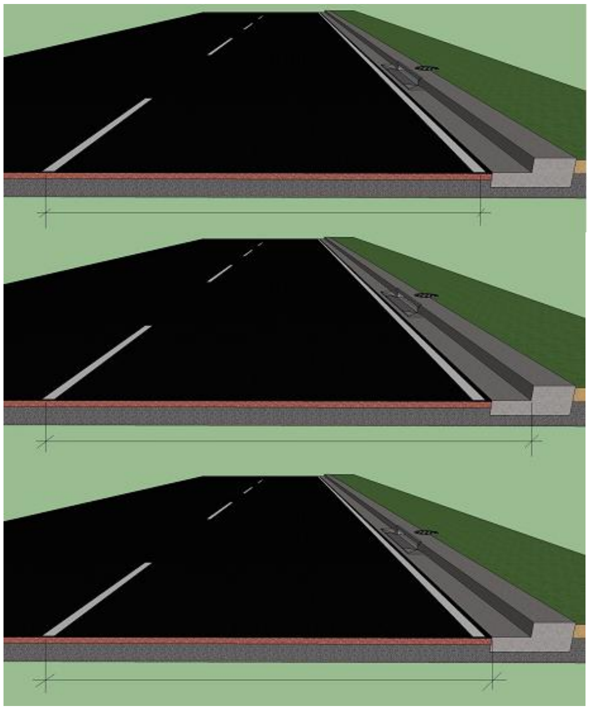


Figure 1 Different methods of measuring lane width – most common method (top diagram), Orlando method (middle diagram) and FDOT standard method (bottom diagram)

Based on prior experience, it was determined that evaluating existing bicycle traffic would not produce sufficient data for the intended analysis. The FDOT districts were contacted to solicit volunteer riders. For liability reasons, riders had to be employees of participating institutions, the universities conducting the research (Florida State University and University of North Florida), or FDOT. Research assistants were used only for operating cameras and collecting speed data.

Sites were screened and only those that had high traffic volume during morning and evening peaks were considered for this study. Sites in these selected cities were further screened to obtain side streets that were suitable for riding and looping back to the beginning point of test section. Table 1 shows characteristics of the corridors that were used for data collection.

As depicted in Table 1, study sites were distributed across the state with speed limits ranging from 30 mph to 45 mph, number of lanes ranging from three (two lanes with a TWLTL median) to six lanes, and outside through lane width of 12.5 ft to 16 ft. Clearly, site characteristics shown in Table 1 are a good representative of various roadway and traffic characteristics of typical asymmetric curb and gutter roadway facilities.

Table 1 Site Characteristics

City	Road name	State Route No.	From	To	No. of lane	Lanes in each direction	Median type	Speed	AADT	Lane Width (feet)		
										Inner	Middle	Outside
Tallahassee	Meridian Rd	SR 155	John Knox Rd	Pinewood Dr	3	1	TWLT	35	15825			12.5
Tallahassee	N Monroe St	SR 63	E 7th Ave	Lake Era Dr	4	2	TWLT	35	29929		11.0	13.5
Tallahassee	Thomasville Rd	SR 61	Grape St	Drive Plaza	6	3	raised	35	26638	10.8	10.8	12.0
Tallahassee	Thomasville Rd	SR 61	Winthrop Dr	Waverly Dr	4	2	raised	45	32501		10.8	16.0
Tallahassee	Thomasville Rd	SR 61	Waverly Dr	Asbury Hill Dr	4	2	raised	45	32501		10.8	16.0
Tallahassee	Thomasville Rd	SR 61	Gardenia Dr	Nimosa Dr	4	2	raised	45	32501		10.8	13.0
St. Petersburg	22nd Ave North		34th St N	32nd St N	4	2	undivided	40	36000		12.0	14.5
St. Petersburg	34th St. S		46 Av. S	50th Ave. S.	6	3	raised	45	28000	12.0	12.0	13.5
St. Petersburg	22nd Ave N		32nd St N	31st St N	4	2	TWLT	40	36000		12.0	14.0
Brandon	Bloomingdale Ave		John Moore Rd.	Van Gogh Cr	4	2	undivided	45	44500		12.0	15.1
Deland	S. Spring Garden Ave	SR 15	Forest Ave	W. Howry Ave	4	2	undivided	45	22500		11.0	14.2
Orlando	US 92	SR 600	Button Rd	Seminal Blvd	4	2	raised	45		12.0	12.0	16.0
Orlando	Aloma Avenue	SR 426	Old Howell Branch Rd.	Howell Branch Rd.	6	3	raised	45	38500		11.0	13.8
Davie	College Ave		SW 39th St	SW 38th St	3	1	TWLT	30	14000			13.5
Boca Raton	N Dixie Highway		SW 18th St	SE 15th St	4	2	Undivided	40	17500	12.0		13.8
Ft. Lauderdale	Sunrise blvd	SR 838	NE 17th Way	NE 17th Ave	4	2	Divided	35	31000	11.0		12.8
W. Palm Beach	N Dixie Highway		Gregory Rd	Alhambra Pl	4	2	Undivided	35	17500	12.0		13.2
Jacksonville	Old Baymeadows Rd		Southside Blvd	Baymeadows Rd	4	2	Undivided	35	25000	12.0		14.0
Jacksonville	Wilson Dr				4	2				12.0		14.0

CHAPTER 4. DATA COLLECTION

The data were collected during peak hour durations in order to collect sufficient interactions of motor vehicles sharing the outside through lane with bicyclists. At each location, cyclists rode along the selected road segment while researchers videotaped their paths and interactions. Video cameras were strategically placed to capture the behavior of a driver as the motor vehicle approached a bicyclist. Efforts were made to hide the camera and camera operator positions from passing traffic in order not to influence driver behavior. Videotaping was done in one direction of traffic at a time. Videotaping was done from behind the cyclists in order to provide the best view of lateral positions of both cyclist and motor vehicle and minimize distraction to drivers. Figure 2 shows the video camera setup with a camera operator hiding behind a pole so that drivers don't recognize that they are being recorded. A one-foot long plastic pipe, as seen in the right hand side photo of Figure 2, was placed at the back of each bicycle to enable scaling of distance measurements in the laboratory.

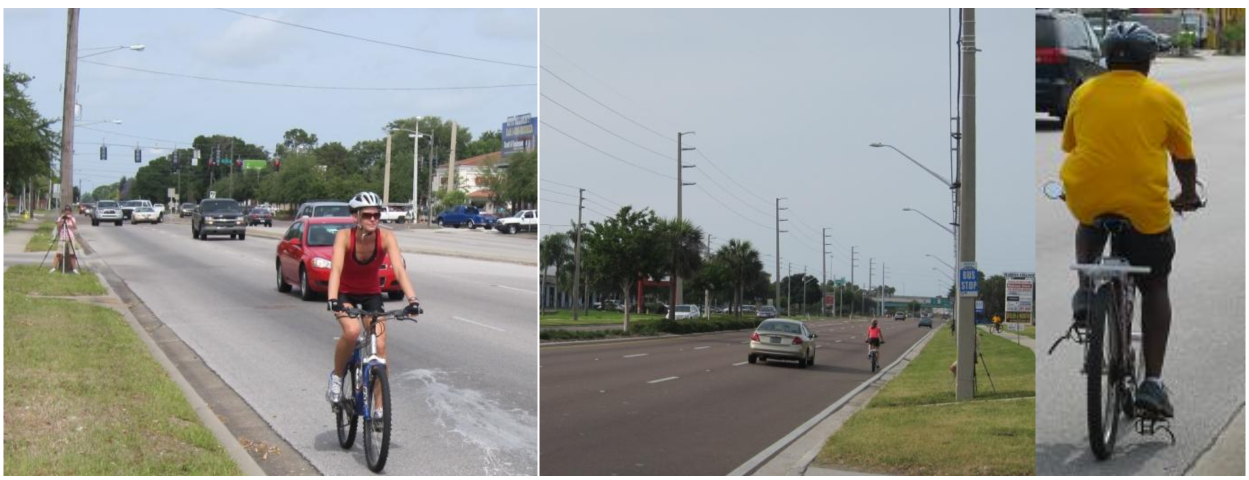


Figure 2 A video camera operator hiding behind the wooden pole (left) and concrete pole (center) to minimize distraction to drivers and a white one-foot-long plastic pipe mounted at the back of the bicycle for scaling purposes (right)

Another camcorder was set up to continuously collect data over the whole length of the segment in order to capture vehicular usage of outside through lanes in the presence or absence of bicyclists. At the same time, one of the researchers was strategically positioned with a laser speed gun to collect spot speeds of motor vehicles during the passing events without being seen by motorists. Three speed variables were recorded: just before passing the bicyclist, while passing the bicyclist, and after passing the bicyclist. At least one pair of speeds (before and while passing, or while passing and after) if not a trio (before, while passing, and after) were collected for each motor vehicle that was spotted to enable a paired-*t* test analysis of the speed data. The type of motor vehicle was also recorded

4.1 Data Reduction

The field videos were taken back to the laboratory where they were cut into shorter lengths and converted to the MPEG-4 video format. Each video segment showed one cyclist riding on one road section. Using Adobe Photoshop CS3, the videos were analyzed for lateral distances between the edge of pavement and cyclist and the cyclist and the motor vehicle body. This was accomplished by first setting a custom measurement scale using the white plastic pipe that was attached to the bicycle as was shown in Figure 2. This allowed the ruler tool to accurately measure lateral distances. Lateral shift was determined visually and estimated to within the closest quartile of the motor vehicle body crossing the lane dividing white stripe (Figure 3).

Figure 3 Lateral shift quartiles of 0-25%, 26-50%, 51-75%, and 76-100% (left to right)

The motor vehicles were classified into six groups: passenger car, SUV, pickup truck, medium truck, large truck, and bus. A medium truck was defined as larger than a pickup truck but smaller than a tractor-trailer. A tractor-trailer was categorized as a large truck. The last three categories did not appear in the videos often enough to allow for statistical analysis. Apart from lateral separation between motor vehicles and bicyclists, distance from bicyclist tire and curb, lateral shift, and motor vehicle type were recorded. Other variables that were recorded during the data reduction process included the gender of bicyclist, bicyclist's type of dress, and the presence of motor vehicles in the inside lane as it might limit lateral shift and lane changing maneuvers.

Not all videos contributed usable data and some only allowed for certain measurements. All of the data were entered into a Microsoft Access database. The complete table of input was then transferred to STATA software for statistical analysis.

CHAPTER 5. ANALYSIS OF RESULTS

5.1 Descriptive Analysis

5.1.1 Lateral Bicyclist Clearance (LBC) From the Curb

Lateral bicyclist clearance was measured as the distance from the center of the bicycle tire to the edge of the curb. The measurement was taken during the time when a motor vehicle was passing the cyclist to allow analysis of this variable on the lateral motor vehicle clearance. The observed lateral bicyclist clearance distances are shown in Table 2. It is interesting to note that at the Monroe site, the lateral bicyclist clearance is about 3.1 ft, which is greater than all other sites. Field observation revealed that this greater LBC is caused by the quality of the joint between the pavement and the curb. At the Monroe site, the pavement was not flush with the curb.

5.1.2 Lateral Motor Vehicle Clearance (LMVC)

Lateral Motor Vehicle Clearance (LMVC) is the distance from the motor vehicle body to the shoulder of a cyclist while passing that cyclist as illustrated by Figure 4. LMVC was measured when the front tire of the bicycle and motor vehicle were parallel on the roadway.

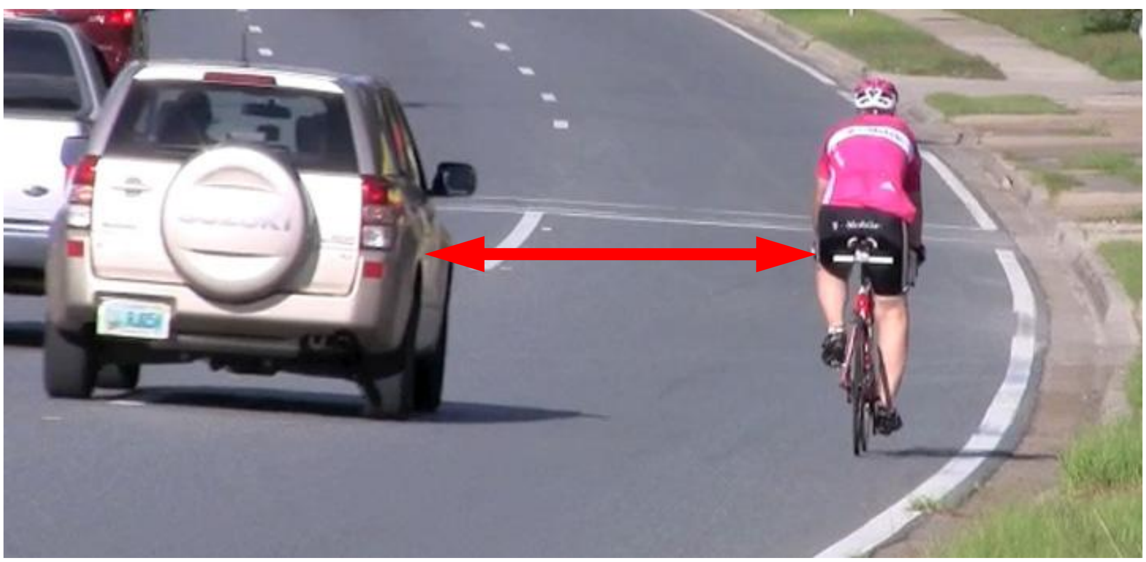


Figure 4 Measurements of lateral motor vehicle clearance from bicyclist

Table 2 presents a statistical summary of site by site results of lateral clearance between motor vehicle and bicyclist. The overall mean LMVC of about 5.2 ft was observed. Two sites, (highlighted rows in Table 3), Meridian Road in Tallahassee and College Avenue in Davie, were observed to have the largest lateral separation, yet they have lane widths of 12.5 and 13.5 ft, respectively, relatively narrow compared to other sites. These two sites are two-lane with a two-way-left-turn (TWLTL) lane median. Most motor vehicles veer to the median to give more distance to bicyclists because in most cases there are no adjacent motor vehicles to cause any lateral conflict.

Table 2 Lateral Clearance from Bicyclist to Curb

City	Road name	From	To	Outside lane width	Sample size	Mean	StDev	Minimum	Maximum
Tallahassee	Meridian Rd	John Knox Rd	Pinewood Dr	12.5	106	1.26	0.32	0.29	2.48
Tallahassee	N Monroe St	E 7th Ave	Lake Era Dr	14.0	83	3.11	0.56	1.83	4.55
Tallahassee	Thomasville Rd	Gardenia Dr	Nimosa Dr	13.5	30	1.93	0.49	0.67	2.83
Tallahassee	Thomasville Rd	Grape St	Drive Plaza	15.8	19	1.23	0.29	0.82	2.09
Tallahassee	Thomasville Rd	Waverly Dr	Asbury Hill Dr	16.0	69	1.14	0.31	0.38	1.88
Tallahassee	Thomasville Rd	Winthrop Dr	Waverly Dr	13.0	114	1.43	0.47	0.58	2.56
St. Petersburg	22nd Ave North	34th St N	32nd St N	14.5	209	2.95	0.50	1.64	4.62
St. Petersburg	22nd Ave N	32nd St N	31st St N	14.0	183	2.42	0.46	1.55	5.54
St. Petersburg	34th St. S	46 Av. S	50th Ave. S.	13.5	124	1.97	0.51	0.53	2.96
Brandon	Bloomingdale Ave	John Moore Rd.	Van Gogh Cr	15.1	118	2.16	0.39	1.33	3.51
Deland	S. Spring Garden Ave	Forest Ave	W. Howry Ave	14.2	124	2.11	0.40	1.21	3.38
Orlando	US 92	Button Rd	Seminal Blvd	16.0	138	2.22	0.39	1.34	3.26
Orlando	Aloma Avenue	Old Howell Branch Rd.	Howell Branch Rd.	13.8	318	2.35	0.41	1.12	4.19
Davie	College Ave	St 39th St	SW 38th St	13.5	59	2.36	0.75	1.20	4.60
Boca Raton	N Dixie Highway	SW 18th St	SE 15th St	13.8	83	2.85	0.61	1.61	4.61
W. Palm Beach	N Dixie Highway	Gregory Rd	Alhambra Pl	13.2	92	2.73	0.77	1.29	5.00
Ft. Lauderdale	Sunrise	NE 17th Way	NE 17th Ave	12.8	116	2.87	0.62	1.75	5.95
Jacksonville	Old Baymeadows Rd	Southside Blvd	Baymeadows Rd	14.0	98	2.18	0.31	1.45	4.01
Jacksonville	Wilson Dr			14.0	102	2.40	0.45	1.60	3.90
Overall					**2185**	**2.26**	**0.69**	**1.12**	**5.95**

Table 3 Lateral Clearance between Motor Vehicle and Bicycle

City	Road name	From	To	Outside lane width	Sample size	Mean	Std. Dev	Minimum	Maximum
Tallahassee	Meridian Rd	John Knox Rd	Pinewood Dr	12.5	106	5.73	1.26	2.90	9.09
Tallahassee	N Monroe St	E 7th Ave	Lake Era Dr	14.0	83	3.11	0.56	1.83	4.55
Tallahassee	Thomasville Rd	Gardenia Dr	Nimosa Dr	13.5	30	5.71	1.71	3.78	11.35
Tallahassee	Thomasville Rd	Grape St	Drive Plaza	15.8	19	5.78	0.92	3.74	7.04
Tallahassee	Thomasville Rd	Waverly Dr	Asbury Hill Dr	16.0	69	5.25	1.44	2.27	9.65
Tallahassee	Thomasville Rd	Winthrop Dr	Waverly Dr	13.0	114	4.74	1.10	2.54	8.68
St. Petersburg	22nd Ave North	34th St N	32nd St N	14.5	209	5.04	1.22	2.65	9.70
St. Petersburg	22nd Ave N	32nd St N	31st St N	14.0	183	5.91	1.51	2.83	11.60
St. Petersburg	34th St. S	46 Av. S	50th Ave. S.	13.5	124	4.84	1.20	2.53	9.24
Brandon	Bloomingdale Ave	John Moore Rd.	Van Gogh Cr	15.1	118	5.95	1.25	3.50	10.61
Deland	S. Spring Garden Ave	Forest Ave	W. Howry Ave	14.2	124	4.89	1.19	2.74	10.53
Orlando	US 92	Button Rd	Seminal Blvd	16.0	138	5.28	0.97	3.09	8.08
Orlando	Aloma Avenue	Old Howell Branch Rd.	Howell Branch Rd.	13.8	318	4.92	1.09	2.06	9.90
Davie	College Ave	St 39th St	SW 38th St	13.5	59	5.79	1.64	3.05	10.88
Boca Raton	N Dixie Highway	SW 18th St	SE 15th St	13.8	83	5.06	1.48	2.91	10.17
W. Palm Beach	N Dixie Highway	Gregory Rd	Alhambra Pl	13.2	92	4.92	1.33	2.00	8.88
Ft. Lauderdale	Sunrise	NE 17th Way	NE 17th Ave	12.8	116	4.41	1.17	2.24	8.58
Jacksonville	Old Baymeadows Rd	Southside Blvd	Baymeadows Rd	14.0	98	5.61	1.35	3.35	10.63
Jacksonville	Wilson Dr			14.0	102	5.43	1.32	2.90	10.22
Overall					**2185**	**5.21**	**1.33**	**2.00**	**11.60**

Figure 5 shows the relationship of lateral separation between bicyclists and motor vehicles. In general, there is a discernible trend of increasing in lateral separation between motor vehicles and bicyclists as the outside through lane width increases. Observations for two sites that are not multilane, Meridian Road in Tallahassee and College Avenue in Davie are not included in Figure 5.

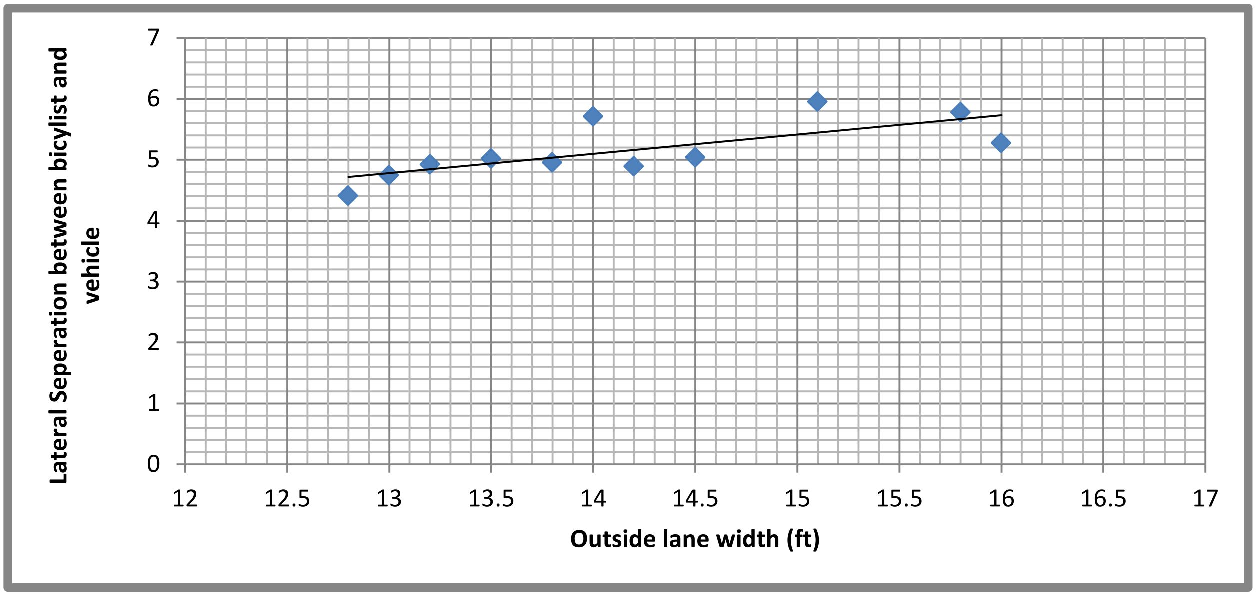


Figure 5 A graph of lateral separation versus outside through lane width

5.1.3 Relationship between Motor Vehicles Lateral Clearance and Bike Position from Curb

The relationship between a motor vehicle's distance from other motor vehicles and the lateral positioning of bicyclists from the curb is depicted in Figure 6. Intuitively, one would expect that the closer you ride to the curb, the more lateral separation you have. On the contrary, the results presented in Table 4 and Figure 6 show that riding closer to the curb results in a smaller separation. Field observations revealed that when bicyclists ride closer to the curb, some motor vehicles, especially compact cars attempt to fit in the lane without laterally shifting to the adjacent lane, hence causing lesser distance. On the other hand, the results show that riding too far from the curb also results in a shorter distance. It seems that there is a spot between 3 and 4 ft from the curb that results in the greatest lateral separation between motor vehicles and bicyclists. It should be noted however, that higher standard deviations were observed. This was mainly caused by the fact that some drivers choose to stay within the outside through lane while others laterally shift to the inside lane.

Table 4 Lateral Clearance and Bicycle Position

Distance to curb (ft)	Distance from body of vehicle to bicyclist (ft)				
	Count	Mean	Standard Deviation	Minimum	Maximum
<2	593	5.0	1.3	2.1	11.6
2-3	487	5.2	1.2	2.1	10.6
3-4	325	5.5	1.4	2.8	10.8
4-5	90	5.3	1.3	2.7	9.1
5-6	29	5.2	1.6	2.8	9.7

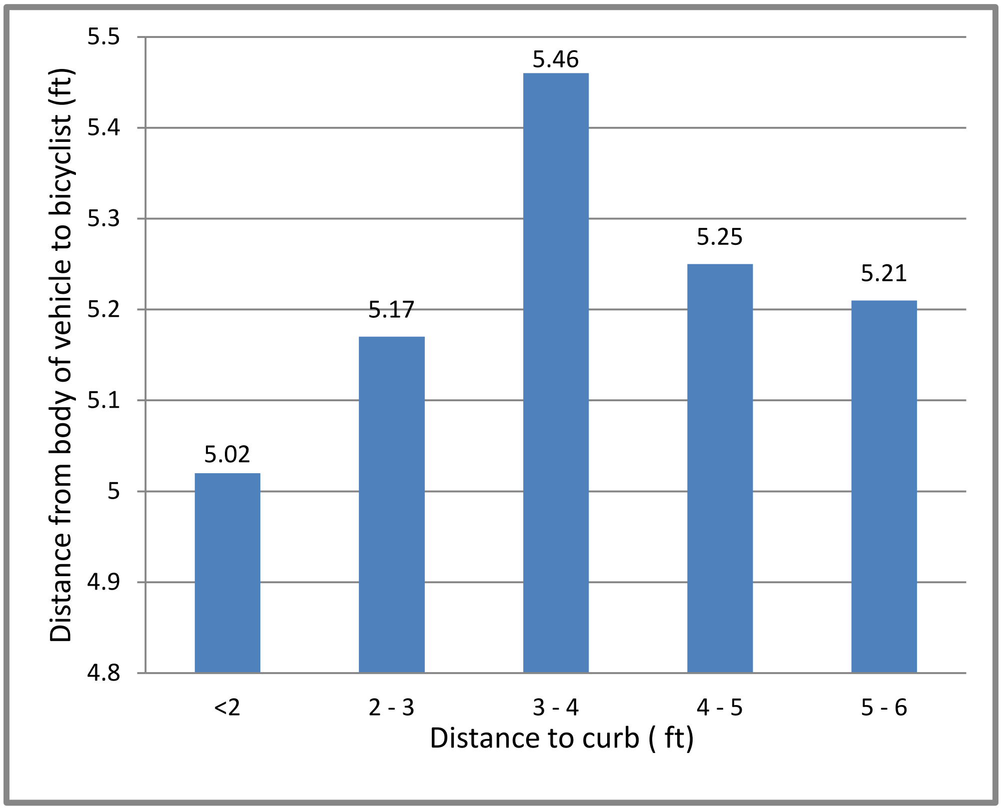


Figure 6 Lateral clearance and bicycle position

5.1.4 Lateral Clearance and Lateral Shift

Mean lateral clearances for motor vehicles that laterally shifted to the inside lane and those that did not shift into the adjacent lane are presented in Table 5. As expected, motor vehicles that laterally shifted to the inside lane left more space compared to those that fitted in the outside through lane while passing a bicyclist. The results presented in Table 5 show that, with an exception of two sites that were not multilane segments, the last two rows (3T sections – two-lane with TWLTL median), lateral clearance increases with lane width. The lower limit of the 95% confidence interval of motor vehicles that did not literally shift to the inside lane for the site with 12.8 ft outside through lane is about 3 ft (from bicyclist body to motor vehicle body). If the motor vehicle mirror is taken into consideration (assume a mirror width of 0.5 ft), the 95% confidence level of the spacing would not allow 3 ft of clearance between a motor vehicle and a bicyclist. This also applies to the site with an outside through lane width of 13.2 ft. Sites with lane widths of 13.5 ft and wider provide sufficient clearance to meet the 3 ft clearance requirement, based on 95% confidence level.

Figure 7 shows the average lateral clearances for vehicles that laterally shifted to the inside lane and those which didn't. The discernible trend of increased clearances flattens when the width of the outside through lane is about 15 ft. It is possible that, for the outside through lane width of 15 ft or wider, motor vehicle-bicycle interaction characteristics do not change much.

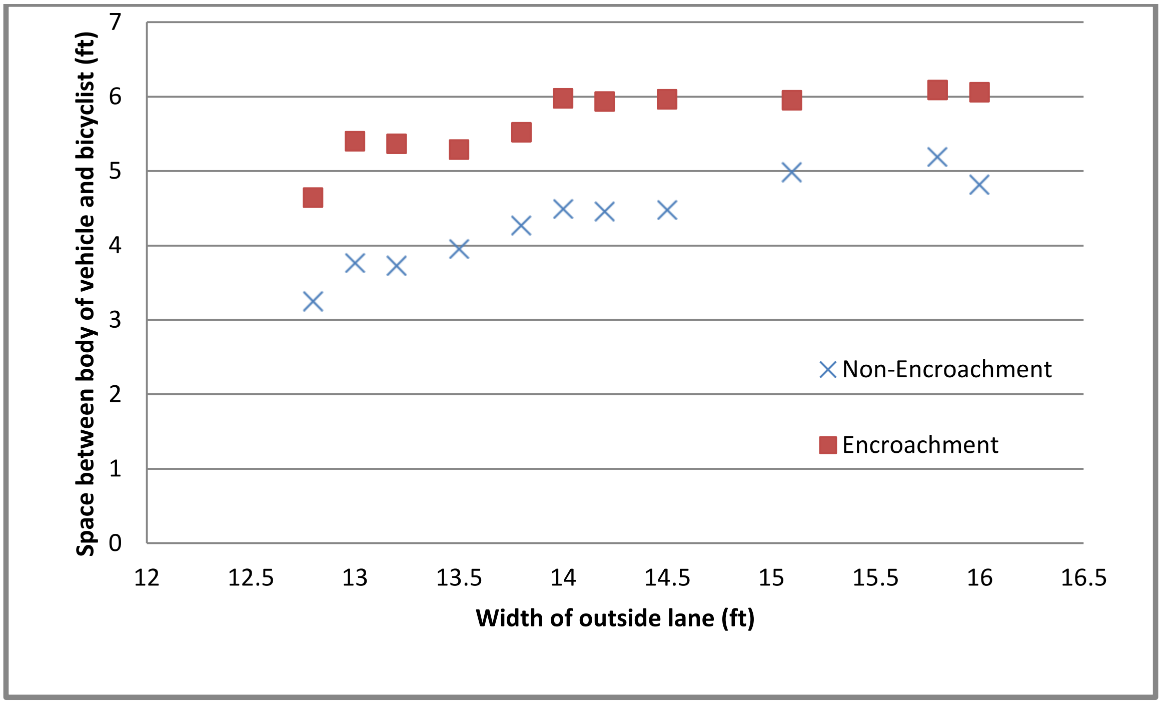


Figure 7 Lateral shift versus lateral clearance

Table 5 Average Lateral Clearance and Lateral Shift

Outside lane width (ft)	Lateral Shift (%)	No Lateral Shift (%)	Lateral clearance								
			Lateral Shift				No Lateral Shift				
			Mean	Std.Dev	Minimum	Maximum	Mean	Std.Dev	Minimum	Maximum	95% confidence interval
12.8	80%	20%	4.64	1.13	2.97	8.58	3.25	0.51	2.24	4.22	3.00 to 3.49
13.0	61%	39%	5.40	0.92	4.00	8.68	3.76	0.51	2.54	4.39	3.60 to 3.92
13.2	71%	29%	5.36	1.23	3.27	8.88	3.72	0.71	2.00	4.66	3.43 to 4.02
13.5	80%	20%	5.29	1.37	3.05	11.35	3.95	0.58	2.53	4.93	3.73 to 4.16
13.8	54%	36%	5.52	1.22	2.95	10.17	4.27	0.65	2.06	5.27	4.17 to 4.36
14.0	82%	18%	5.98	1.42	2.83	11.60	4.49	0.60	2.90	5.49	4.34 to 4.63
14.2	71%	29%	5.93	1.40	3.64	10.53	4.45	0.76	2.74	5.61	4.29 to 4.62
14.5	63%	37%	5.96	1.30	2.65	9.70	4.47	0.73	2.78	6.25	4.34 to 4.60
15.1	51%	49%	5.95	1.25	3.50	10.61	4.98	0.59	3.50	6.13	4.82 to 5.14
15.8	39%	61%	6.09	0.70	4.88	7.04	5.19	1.05	3.74	6.37	4.22 to 6.16
16.0	37%	63%	6.06	1.21	2.92	9.65	4.81	0.82	2.27	6.42	4.67 to 4.96
*12.5	96%	4%	5.78	1.23	2.90	9.09	3.30	0.21	3.15	3.44	
*13.5	90%	10%	6.01	1.57	3.59	10.88	3.83	0.60	3.05	4.75	

*The bottom two sites are 3T (two-lane with TWLTL median)

5.1.5 Lateral Clearance and Restriction

Figure 8 presents analysis of lateral clearance for interactions that involved restricted and unrestricted gaps. Drivers that passed bicyclists when there was no other motor vehicle nearby in the inside lane provided more separation (about 1.34 ft more on average) than those that passed bicyclists during restrictive lane changing conditions. It was observed that in most cases, when there was no motor vehicle in the inside lane, drivers would shift to the inside lane or change lanes completely while passing the bicyclist.

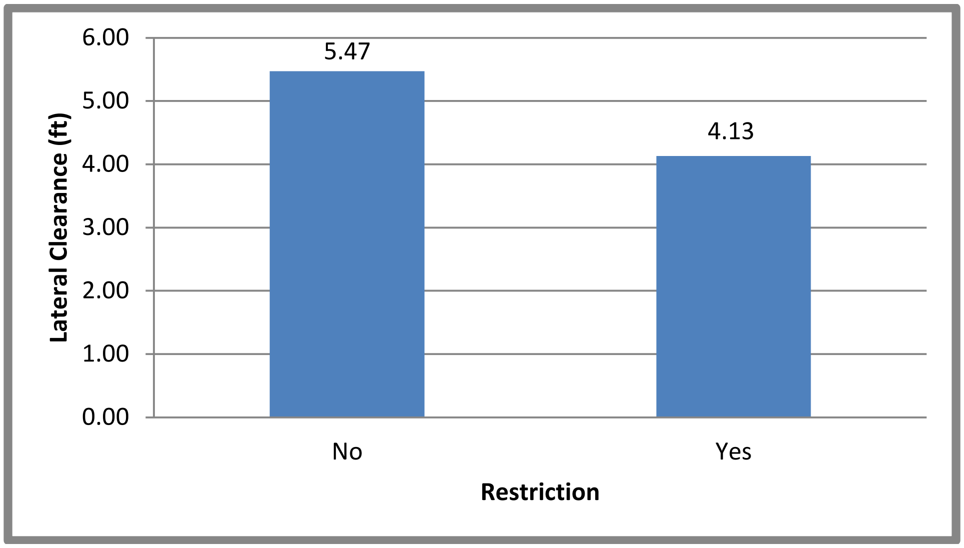


Figure 8 Restriction versus lateral clearance

5.1.6 Lateral Clearance and Gender

The analysis was conducted to determine if gender has any effect on lateral clearances provided by motorists passing bicyclists. Figure 9 shows average lateral clearances by gender type. The results show that motorists give female riders more space than male bicyclists during the passing event. An average lateral clearance of 5.12 ft for male riders and 5.59 ft for female riders was observed.

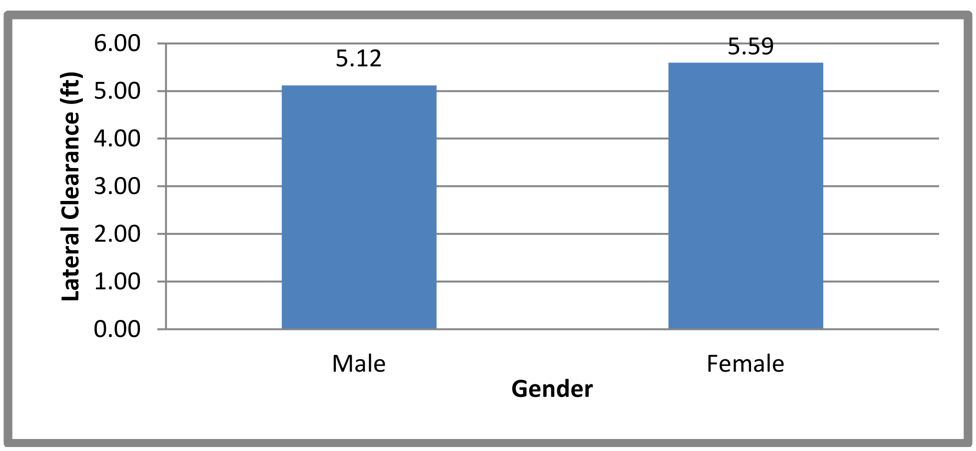


Figure 9 Gender versus lateral clearance

5.1.7 Lateral Clearance and Athletic Outfit

Average clearances as a function of rider's outfit are presented in Figure 10. On average, motorists provided slightly more space when passing the cyclist who was not dressed in bicycle attire. Although it could not be determined why drivers provided more space for casually dressed cyclists, it is possible that motorists perceived less risk passing riders who were in bicycle outfit.

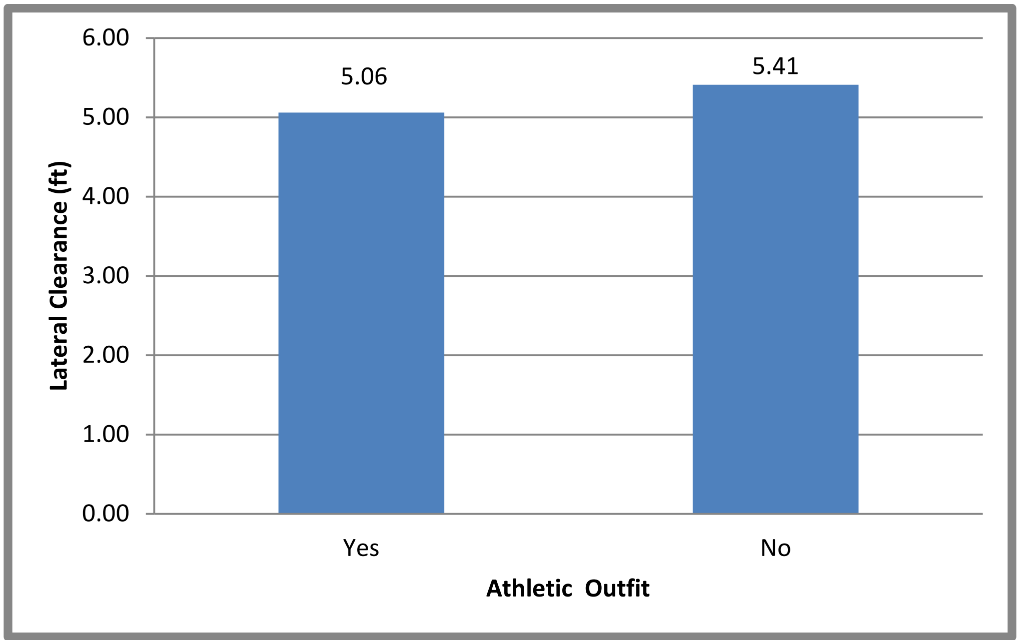


Figure 10 Gender versus lateral clearance

5.1.8 Lateral Clearance and Motor Vehicle Type

One would expect that the space between a motor vehicle and a bicycle during a passing event would be a function of the size of the motor vehicle. Intuitively, one assumes that larger motor vehicles would pass closer than passenger cars. According to field observations, this assumption is not necessarily true. Table 6 shows lateral clearances by motor vehicle type. Table 6 clearly shows that, on average, medium trucks pass closer to bicyclists than other types of motor vehicles. Also, it was observed that buses allow less lateral clearance than large trucks. Examination of the video tapes revealed that there were bus stops downstream of the majority of bus-bicycle interactions. Therefore buses shifted to inside lane just enough to pass bicycles and then returned to the outside through lane to avoid lane changing closer to bus stops. On the other hand, although passenger cars are smaller than SUVs and pickup trucks, on average, they left less space while passing bicyclists. This was due to the fact that more passenger cars tried to fit in the outside through lane. Most large trucks either moved into the inside lane or changed lane while passing, which resulted in the largest clearance of all motor vehicle types (6.27 ft).

5.2 Descriptive Statistics for Modeling Data

Modeling involved videotapes of 2185 observations of bicyclist and motorist passing events. The descriptive statistics of the data are displayed in Table 7. The overall average lateral distance from the body of the motor vehicle to the body of the bicyclist was 5.21 ft. The mean distance from the bicyclist's tire to the face of the curb was 2.26 ft. These values correspond with what was reported by Harkey *et al*. (1996) – that is, average spacing of 6.4 ft and bicycle positioning of 1.4 ft from the edge of the roadway for wider outside through lanes. Nearly a foot difference for lateral separation might be attributed to the fact that Harkey *et al.* measured the separation to the center of the bike tire while this study considered the lateral separation to be between the fender of the motor vehicle to the left shoulder of the bicyclist (See Figure 4). If the shoulder point was too high to achieve an accurate measurement from the video, the separation was measured from the cyclist's hip.

The difference for bicycle positioning between this and previous studies might be due to the difference between a reference point used, i.e., the study by Harkey *et al*. measured bicycle positioning from edge of pavement while this study measured it from face of curb. The majority of roadways tested in this study were state highways, with an 18" separation between edge of pavement and face of curb. Normally, face of curb is about 1 to 1.5 feet from edge of pavement depending on the type of curb used.

Table 6 Lateral Clearance (ft) by Motor Vehicle Type

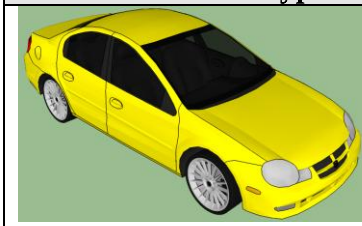
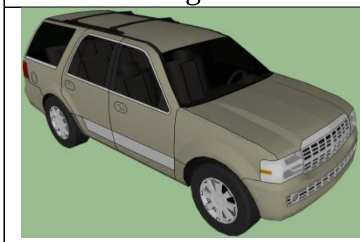
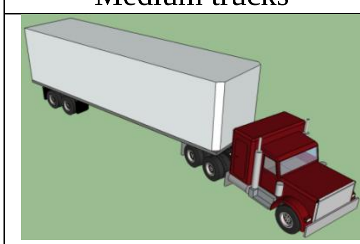
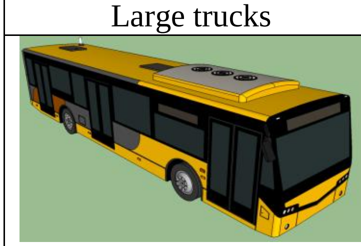
Motor Vehicle Type	N	Mean	Std. Dev	Minimum	Maximum
 Passenger cars	1238	5.19	1.30	2.00	11.35
 SUVs	425	5.30	1.37	2.27	11.60
 Pickup trucks	336	5.25	1.26	2.75	9.24
 Medium trucks	47	4.48	1.47	2.12	10.61
 Large trucks	19	6.27	2.30	3.39	10.53
 Buses	8	4.79	0.99	3.22	6.45

Table 7 Descriptive Statistics of Model Variables

CONTINUOUS VARIABLES						
Explanatory Variables	Categories	Explanation	Average (ft)	Standard deviation	Minimum (ft)	Maximum (ft)
Lateral Motor Vehicle Clearance (LMVC) (ft)	Continuous variable	Lateral separation from body of motor vehicle to body of bicyclist	5.21	1.33	2.00	11.60
Lateral Bicycle Clearance (LBC_ (ft)	Continuous variable	Distance from bicyclist tire to the end of curb	2.26	0.69	0.29	5.95
Width of outside Lane (ft)	Continuous variable	Distance from edge of pavement to the center of stripe the inside lane	13.97	1.15	12.00	16.00

CATEGORICAL VARIABLES			
Explanatory Variables	Categories	Explanation	Percentage (%)
Motor vehicle type	0	Passenger vehicle	59.72
	1	Sport utility vehicle (SUV)	20.50
	2	Pickup truck	16.21
	3	Medium truck	2.27
	4	Large truck	0.92
	5	Bus	0.39
Gender	0	Male	79.50
	1	Female	20.50
Dress	0	Athletic	36.85
	1	Non-athletic	63.15
Lateral shift level	0	No lateral shift	45.65
	1	About 0% to 25% of motor vehicle body laterally shifting to the adjacent lane	44.56
	2	About 25% to 50% of motor vehicle body laterally shifting to the adjacent lane	7.37
	3	About 50% to 75% of motor vehicle body laterally shifting to the adjacent lane	1.57
	4	About 75% to 100% of motor vehicle body laterally shifting to the adjacent lane	0.86
Restriction	0	No motor vehicles in adjacent lane, motor vehicle can change lane to avoid close interaction with bicyclist	67.82
	1	Motor vehicles present in adjacent (inside) lane, motor vehicle cannot change lane to avoid close interaction with bicyclist	32.18

The average lane width of the overall dataset was 13.97 ft. Table 7 also shows that about 96.43% of motor vehicles were passenger cars, sport utility vehicles, and pickup trucks (59.72%, 20.50%, and 16.21%, respectively). Other motor vehicle types such as buses, medium trucks and large trucks were very few (about 3.57% in total) and were therefore not included in the model. Table 7 also shows that 79.5% of data were extracted from male bicyclists while 20.5% of the data came from female riders.

Among other descriptive statistics in Table 7, riders wearing athletic clothing (bicycle outfit) accounted for 36.85% while those dressed in normal clothing were 63.15%. As far as lateral shifting is concerned, about 45.65% of motor vehicles did not move to the adjacent lane when passing bicyclists while 44.56% of the motor vehicles had about 0% to 25% of their bodies shifting into the adjacent lane. About 67.82% of the motor vehicles passed bicyclists when there were no motor vehicles in the inside lane to restrict partial lateral shift or lane changing maneuver if desired while 32.18% of the motor vehicles shared the outside through lane with bicyclists in the presence of motor vehicles riding adjacent or in close proximity in the inside lane, restricting the possibility of lateral shift or changing lanes.

5.3 Model Estimation for Distance from Body of Motor Vehicle to Body of Bicyclist

A regression model was developed for the distance from body of motor vehicle to body of bicyclist. The STATA statistical package was used for the regression model runs. Model coefficients and their significance levels are provided in Table 8. The results in Table 8 suggest that passenger vehicles keep a closer lateral distance to bicyclist than pickup trucks and SUVs. The results also suggest that among the three motor vehicle types, SUVs maintain the greatest lateral separation to bicyclists. As for gender comparison, the results indicated that motorists are more courteous to female than male riders. The lateral separation for female riders was significantly greater than for male bicyclists. This finding is consistent with that of Walker (2007). The study by Walker compared lateral separation between motor vehicles and bicyclists by having a short-haired male rider first ride with his natural hair and then put on a long feminine wig in order to appear as a female to drivers approaching from upstream. It was found that drivers left more space when passing a male bicyclist appearing as a female bicyclist.

Table 8 Parameter Estimates of Lateral Motor Vehicle Clearance Regression Model

Variable	Coefficient	Standard Error	*t*-statistic	*p*-value
SUVs	0.027964	0.068006	0.41	0.681
Pickup trucks	0.018129	0.073867	0.25	0.806
Medium trucks	-0.7126	0.178167	-4	0
Gender (female)	0.15357	0.068856	2.23	0.026
Dress (non-athletic)	0.17684	0.156675	1.13	0.259
Outside lane width (ft)	0.073447	0.019169	3.83	0
Distance of bike tire to curb	-0.05922	0.059548	-8.26	0
Restriction	-0.49189	0.045249	-1.31	0.191
Lateral shift level	0.893303	0.277244	2.9	0.004
Constant	4.012533	0.333091	12.05	0

Other factors that were found to be significant were the outside through lane width and the presence of motor vehicles in the proximity of the passing event, restricting lane changing maneuver. The increase in outside through lane width was associated with greater lateral separation. On the other hand, restrictive lane changing conditions resulted in motor vehicles leaving less space while passing bicyclists. Intuitively, one would expect that the closer to the curb the bicyclists ride, the greater would be the separation between motor vehicles and bicyclists. Although the results are in agreement with this supposition, the data shown in Table 8 suggest that the distance of bike tire to the curb is not significant in predicting the lateral separation between motor vehicles and bicyclists. Some bicyclists were dressed in bicycle outfits (athletic attire) while others were in non-athletic dress. The data show that drivers leave more space for non-athletically dressed riders than athletically attired bicyclists. However, the dress type was not statistically significant

5.4 Regression Modeling for Motor Vehicle Lateral Shift

This second multivariate regression model describes the motorist lateral shift as a function of factors such as width of outside through lane, motor vehicle type, gender, dress, and the presence of motor vehicles in the inside lane while the motor vehicle in outside through lane passes the bicyclist (restriction). Table 9 summarizes the results of motor vehicle lateral shift modeling analysis. The results suggest that the level of lateral shift decreases with an increase in the width of the outside (curb) lane. Compact motor vehicles were observed to have less lateral shift than other types of motor vehicles. In general, the level of lateral shift was greater when motor vehicles passed female riders than when passing male bicyclists. The results also indicate that the further the bicyclists were riding from the curb, the more the motorists laterally shifted into the adjacent lane. Less lateral shift was observed when motor vehicles were present in the inside lane at the passing event – when the passing motor vehicle was restricted by adjacent motor vehicles, not having enough gap to move either partially or fully to the inside lane while passing the riders. The model results suggest that dress type is not significant in predicting lateral shift behavior.

Table 9 Parameter Estimates of Extent of Motor Vehicle Lateral Shift Regression Model

Variable	Coefficient	Standard Error	*t*-statistic	*p*-value
Sport Utility Vehicle (SUV)	0.19	0.04	4.96	0.00
Pickup truck	0.10	0.04	2.41	0.02
Medium truck	0.32	0.10	3.12	0.00
Gender (female)	0.09	0.04	2.27	0.02
Dress (non-athletic)	0.14	0.09	1.55	0.12
Outside lane width	0.15	0.01	14.14	0.00
Distance of bike tire to curb	0.38	0.24	2.63	0.01
Restriction	-0.44	0.03	-13.39	0.00
Model constant	-1.91	0.19	-10.12	0.00

5.5 Lane Usage

Site observations revealed that motor vehicles moved to the inside lane after realizing the presence of a bicyclist from upstream. A lane usage factor was therefore computed to illustrate this phenomenon. A lane usage factor accounts for uneven distribution of motor vehicles among lanes when two or more lanes are available for a movement. Figure 11 illustrates motor vehicle lane usage behavior in the absence and presence of motor vehicles. In the absence of a bicyclist (left photo) a considerable number of motor vehicles were observed to use the outside through lane. Conversely, a certain percentage of motor vehicles shifted to the inside lane before passing the bicyclist to avoid sharing the outside through lane with a bicyclist as seen in the right hand side photo in Figure 11.

Figure 11 Outside through lane usage in the absence of bicyclist (left) and in the presence of bicyclist (right)

Table 10 shows the results of motor vehicle outside through lane usage computations. The data show that when bicyclists are not present, approximately 56% of motor vehicles use the outside through lane whereas only about 40% of motor vehicles use the outside through lane when a bicyclist is riding on the outside through lane for four-lane corridors. Uneven distribution of motor vehicles was also observed for six lane segments. For six lane segments, the motor vehicle outside through lane usage dropped from approximately 31% to about 26% when bikers were present. The results show a pattern of motor vehicles shifting to the inside lane to avoid sharing the wider outside through lane with bicyclists when conditions allowed for safe lane changing maneuver. The shift was even more pronounced when traffic volume was low.

Table 10 Lane Usage Results

Segment type	Situation	Number of observations	Lane Utilization		
			Outside lane	1st Inside lane	2nd inside lane
4 lane segments	Bicyclist present	156	40.2%	59.8%	N/A
	No bicyclist	402	56.2%	43.8%	N/A
6 lane segments	Bicyclist present	143	25.70%	38.7%	35.60%
	No bicyclist	279	30.60%	36.30%	33.10%

5.6 Motor Vehicle Speed

The analysis of vehicular speeds during the passing events was completed by using speed data that were collected for the three scenarios: just before passing the bicyclist, while passing the bicyclist, and after passing the bicyclist. Only passenger cars, vans, and pickup trucks were analyzed because other motor vehicle types were not enough to provide sufficient data for analysis. Table 11 shows the average and standard deviations of the observed spot speeds for each of the three scenarios. In general, data suggest that motor vehicles slow down as they pass bicyclists and increase their speeds after the passing event.

Table 11 Motor Vehicle Speed Results

Vehicle type	Vehicle Position					
	Before		Passing		After	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Passenger car	35.70	6.36	33.10	7.16	37.29	6.30
Van	35.25	6.58	33.63	6.32	37.57	4.47
Pickup truck	34.67	2.08	32.00	4.82	37.89	3.72
Truck	28.87	7.51	31.50	8.80	32.75	4.59
Combined	**34.13**	**6.80**	**32.76**	**7.08**	**36.86**	**5.53**

Overall statistics

Observations	Mean	Standard deviation	Minimum	Maximum
589	**34.13**	6.13	13	50

Paired-*t* test Results for Speed Data

Event comparison	*t*-statistic	*p*-value	Reject null?
Before and passing	2.15	0.069	No
Passing and after	-6.81	0.000	Yes

*All speed values in miles per hour

For each motor vehicle, speed for before, passing, and after was to be recorded. Due to site limitations, in some cases only before and passing, or passing and after speeds were recorded. Speeds for the three scenarios were therefore compared using a paired-*t* test. This test is appropriate for analyzing samples that have two different treatments, i.e., paired treatments. In this case, paired treatments include before and passing, and passing and after scenarios. The paired-*t* test provides the statistic, which is used to determine if there is a significant difference between the speeds of each motor vehicle for the paired scenarios. The null hypothesis for this test represented the proposition that the spot speeds of the above mentioned scenarios are equal while the alternative hypothesis is that the speeds are not equal. The alternative hypothesis is accepted only when the data suggest sufficient evidence to support it, hence rejecting the null hypothesis. All paired scenarios were tested at the 95% confidence level.

The results of the paired-*t* test are shown in the lower portion of Table 11. At 95% confidence level, data shows sufficient evidence to indicate that the motor vehicles increase their speeds after passing bicyclists. On the other hand, the results suggest that the observed slowing down of motor vehicles during the passing event is not significant at 95% confidence level. It is possible that the difference between before and passing is not significant because drivers start reducing speed in advance while trying to make a decision whether to stay in the outside through lane, laterally shift to the adjacent lane, or completely move to the inside lane. It should be noted however that the *p*-value of 0.069 means that if the data were tested at 90% confidence level, the difference of the before and passing events would be significant. Figure 12 is a graphical presentation of the summary of data shown in Table 11, to reiterate the phenomenon of motor vehicles reducing speeds as they approach the bicyclists and increasing speed afterwards.

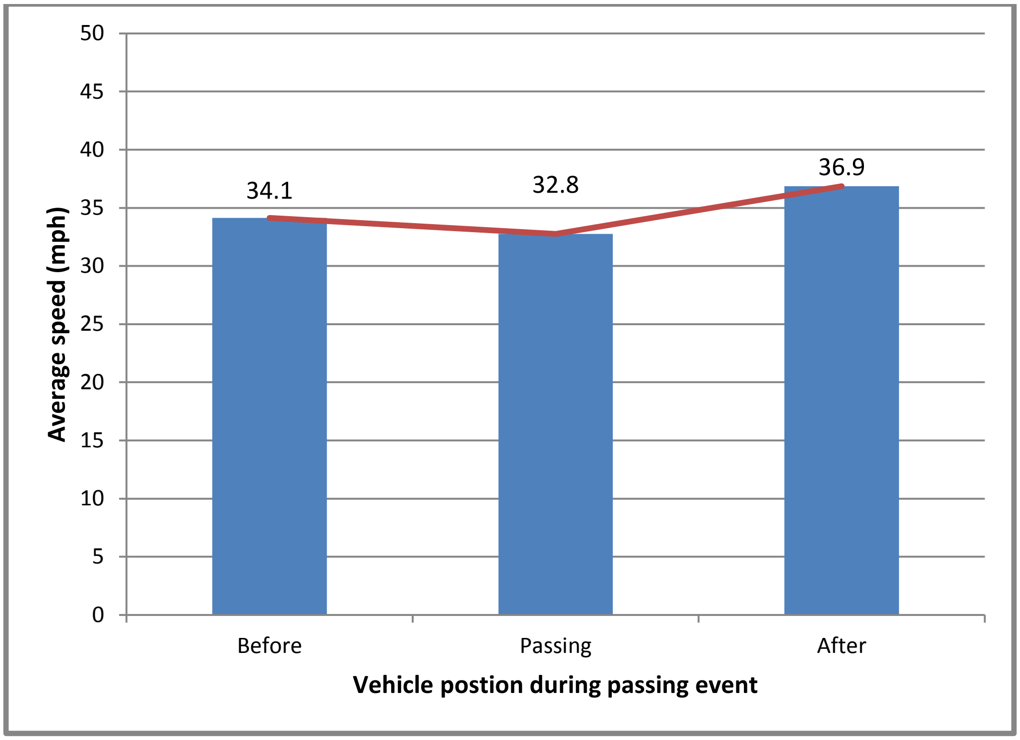


Figure 12 Average speed by event type

CHAPTER 6. SUMMARY OF FINDINGS

The study reported herein was conducted to examine the influence of different site characteristics on the interaction between motor vehicles and bicyclists. Four main measures of effectiveness were studied: lateral separation between motor vehicles and bicyclists, motor vehicle lateral shift to the adjacent inside lane, usage of the outside through lane, and motor vehicle speeds before passing, while passing, and after passing bicyclists.

The research results show that passenger cars drive closer to bicyclists than other motor vehicle types. The data also suggest that motorists are more courteous to female bicyclists. The results further indicate that the wider the outside through lane width, the more the lateral separation between motor vehicles and bicyclists. It was observed that the higher the vehicular traffic level, the closer to the bicyclists the motor vehicles ride due to the fact that they have to stay in the outside through lane without laterally shifting or changing lanes. Due to the same reason, motor vehicles leave less room to bicyclists when motor vehicles are present in the inside lane, in the proximity of the passing event. The farther out into the road the riders cycle, the less space they receive from passing motor vehicles. However, modeling results suggest that the difference is not statistically significant.

Most of the factors that were found to be significant in explaining the lateral separation between motor vehicles and bicyclists were also significant in the motorist lateral shift model. Pickup trucks and SUVs were observed to have higher amounts of lateral shift than passenger cars and the lateral shift amount was less in restricted lane changing and high traffic level conditions. The amount of the motor vehicle body laterally shifting to the inside lane was reduced with the increase in the width of the outside through lane.

The results of descriptive statistics, 95% confidence intervals, and regression modeling, all point out that lateral spacing between motor vehicles and bicyclists is highly influenced by the width of the outside through lane. A typical width for outside through lane is 14 ft. Based on 95% confidence intervals, outside through lane widths less than 13.5 ft could result in a significant decrease in lateral spacing, especially for motor vehicles that share the outside through lane without laterally shifting to the inside lane.

The results further show that, given acceptable gaps, motorists tend to move from the outside through lane to inside lane after recognizing that there is a bicyclist downstream. It was interesting to note that on average, drivers reduce their speeds when passing bicyclists to ensure safe passing maneuver and then accelerate after passing bicyclists.

CHAPTER 7. RECOMMENDATIONS FOR FUTURE RESEARCH

Although this study evaluated lateral separation between motor vehicles and bicyclists during passing events, it did not determine what separation bicyclists feel comfortable with or whether there are individual differences based on factors such as gender and age. A future study on the bicyclists' perception of motorists' passing behaviors could be meritorious.

This study considered the lateral separation to be the distance from the body of the motor vehicle to the body of the bicyclist. This was due to the definition of lateral clearance provided by Florida three feet clearance law. Clearly, the right hand side motor vehicle mirror is closer to the bicyclist than the motor vehicle body. It is therefore suggested to look into whether the lateral separation should be considered to be the distance from the closest part of the motor vehicle to the body of the bicyclist, which in most cases would be the mirror.

Future research should establish the reasons behind some of the findings of this study. For example, it is not clear whether motorists rode further from bicyclists dressed in normal clothing than they did for riders in bicycle outfits because they felt that riders with bicycle outfits are more predictable as they look more professional than riders who were dressed normal.

Some of the measures of effectiveness that were analyzed in this study, such as motor vehicle wide lane usage and spot speeds, provide an understanding of operational characteristics of asymmetric curb and gutter roadways but do not provide parameters that could be directly used for traditional design and traffic operational studies. Determination of more direct measures of effectiveness such as vehicular density per lane and space mean speeds in lieu of lane usage and spot speeds could profitably be explored in future study as they can be easily adopted in traffic engineering practice, such as vehicular level of service (LOS) studies.

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PART B: SAFETY ANALYSIS

CHAPTER 1. INTRODUCTION

This portion of the report presents the process used in developing Crash Modification Factors (CMFs) that describe change in safety when a typical roadway, measuring 12 ft for both inside and outside through lanes, is changed to an asymmetric section, a narrower inside lane and wider outside through lane (asymmetrical lane width configurations/ asymmetric curb and gutter roadways). An example of this would be restriping a 12 ft inside and outside through lane to an 11 ft inside lane and 13 ft outside through lane, rendering the outside through lane a shared lane for bicycles and motor vehicles. The following sections provide a narrative of the problem background, research need, research objectives, and report organization.

1.1 Research Need

The evaluation of treatment effect is essential to the process of developing countermeasures. Crash Modification Factors (CMFs) are used to quantify the change in expected average crash frequency (crash effect) at a site caused by implementing a particular treatment (also known as a countermeasure, intervention, action, or alternative), design modification, or change in operations. CMFs reflect the recognition that a change in geometry, traffic control device or signalization could result in either an increase or a decrease in crashes. The Highway Safety Manual (HSM, 2010) provides a list of CMFs for different geometric features such as lane width, shoulder width, and median width. However, CMFs for lane widths reported in the Highway Safety Manual are for rural highways only. None of the CMFs were developed specifically to address the safety consequences of lane width for urban roadways. Thus, this study was initiated to develop CMFs for lane width, specifically, for asymmetric curb-and-gutter roadways.

1.2 Research Objectives

The objective of this part of the study was to fill some of the knowledge gap regarding state-of-knowledge and state-of-the-practice in highway safety, specifically focusing on curb-and-gutter multilane asymmetrical lane width configurations. Two main research goals guided this study

1. Development of crash prediction models (Safety Performance Functions) for curb-and-gutter multilane roads with asymmetrical lane width configurations.
2. Development of crash modification factors (CMFs) for curb-and-gutter multilane roads with asymmetrical lane width configurations.

CHAPTER 2. LITERATURE REVIEW

A survey of the published literature was conducted through various literature search sources. The literature search revealed paucity of literature on crash modification factors (CMFs) of lane width for urban multilane roads. A summary of the detailed literature review follows. The sections are divided into two main parts. The first covers literature on CMFs, while the second describes literature on safety performance functions (SPFs).

2.1 Methods Used to Develop Crash Modification Factors

A review of the literature revealed two fundamental approaches commonly used in developing CMFs. These approaches are (1) Before-and-after studies, and (2) Observational cross-sectional studies. The following section provides details on these two approaches.

2.1.1 Before-and-After Studies

According to previous research, the best scientific approach for assessing the safety effectiveness of a given type of treatment, or combination of treatments, on a roadway segment or intersection is through conducting Empirical Bayes (EB) before-and-after evaluations. This method is generally preferred where appropriate data is available. The information obtained from evaluation provides feedback for the process of planning future safety improvements. Other well-known types of before-and-after studies include observational before-and-after studies using comparison groups and experimental before-and-after studies. A detailed discussion of each method can be found in the following subsections.

2.1.1.1 Observational Before-and-After Study Using Empirical Bayes (EB)

Empirical Bayes (EB) method is broadly discussed by Hauer (1997). As described in the Highway Safety Manual (HSM, 2010), the EB method combines a site's observed crash frequency and SPF-based predicted average crash frequency to estimate the expected average crash frequency for that site in the after period had the treatment not been implemented. The comparison of the observed after crash frequency to the expected average after crash method estimated with the EB method is the basis of the safety effectiveness evaluation. The National Cooperative Highway Research Program (NCHRP Report 617, 2008) observes that the Empirical Bayes methodology has been employed in various recent studies because of its ability to (1) properly account for regression to the mean problem, (2) overcome the difficulties of using crash rates in normalizing for volume differences between the before-treatment and after-treatment periods, (3) reduce the level of uncertainty in the estimate of safety effect, (4) provide a foundation for developing guidelines for estimating the likely safety consequences of the contemplated implementation of the evaluated treatment, and (5) properly account for differences in crash experience and reporting practice in amalgamating data resulting from diverse jurisdictions.

2.1.1.2 Observation Before-and-After Study Using Comparison Groups

Observational before-and-after studies using comparison groups use non-treated sites as a comparison group. The purpose of the comparison group is to estimate the change in crash frequencies that would have occurred at the treated sites if the treatment was not implemented.

This method uses an approach similar to EB in developing CMFs. However, the comparison sites are used to predict estimated crash frequency instead of SPF.

2.1.1.3 Experimental Before-and-After Study

Experimental before-and-after studies refer to the use of a set of sites which have similar geometric features and relatively similar traffic volumes for the experiment. The sites are randomly assigned to treated or to non-treated groups. Treatments are then applied to some of the sites in the treated group; then crash and traffic volume data are collected for the periods before and after treatment. Subsequent differences in crash frequency between the treatment and comparison groups are directly attributed to the treatment. These types of studies are very common in the field of medicine. However they are rarely conducted in the field of safety improvement due to their random nature. Most of highway safety officials tend to avoid a random selection of sites for improvement as it results in omission of high ranked problem sites.

2.1.2 Cross-Sectional Studies

When it is deemed impractical to perform before-and-after studies, cross-sectional evaluations are conducted. The cross-sectional method is employed when comparing the safety performance of a roadway with certain special features to the safety performance of another roadway without these special features. The study by the National Cooperative Highway Research Program (NCHRP Report 617, 2008) found this method to be useful when evaluating the safety effects of a roadway cross-section where the change of one feature results in the change of another. For instance, widening or reducing median width normally affects other geometric features like shoulder width. The cross-section method was also considered appropriate (HSM, 2010) when dealing with a treatment situation whose before-treatment information could not be obtained. This method consists of estimating CMFs using the coefficients of regression models. Details of statistical techniques and methodologies that have been used in cross-sectional studies are broadly discussed by Li *et al*. (2009).

2.2 Safety Performance Functions

Safety performance functions (SPFs) are regression equations that relate the expected crash frequency at a site to the various traffic and geometric characteristics of that site. Poisson and Negative binomial are widely used for developing SPFs because these modeling techniques are able to analyze data while preventing the possibility of a negative integer crash value over a length of time.

2.3 Selection between Poisson and Negative Binomial when Developing Safety Performance Functions

Previous studies have used Poisson distribution to estimate the expected number of crashes (Miaou *et al.*, 1992; Joshua and Garber, 1990). However, the underlying assumption of Poisson theorem, having equal values for mean and variance, has proved invalid for data used in most safety modeling studies. In most cases, over-dispersion on data was observed. This phenomenon led to the adoption of negative binomial (NB) as an alternative modeling technique.

However, before illustrating the negative binomial (NB) regression model, it is important to discuss the formulation of the Poisson model. The Poisson model is defined by the following equation:

$$P\ \ y_i\ \ = \frac{\lambda_i^{y_i}\ exp\ \ \lambda_i}{y_i!} \qquad 1$$

Where

P (y_i) =the probability of y crashes occurring on a highway segment i,

λ_i = the expected crash frequency, i.e., E (y_i)) for highway segment i.

It is worth mentioning that, when applying the Poisson model, the expected crash frequency is assumed to be a function of explanatory variables such that

$$\lambda_i = \exp(\beta X_i) \qquad (2)$$

Where

X_i = vector of predictors such as geometric and traffic characteristics of roadway segment i that determine crash frequency

β = vector of estimable coefficients.

A standard maximum likelihood method is used to estimate the coefficient vector β. Likelihood function, L (β), together with (equations 1 and2) results to:

$$L\ \ \beta\ \ = \quad {}_i \frac{exp\ -exp\ \ \beta X_i\ \ \ [exp\ \ \beta X_i\ \ ]^{y_i}}{y_i!} \qquad (3)$$

To take into account dispersion, an error term ε_i is introduced to the expected crash frequency (λ_i) such that equation (2) becomes

$$\lambda_i = \exp\ \ \beta X_i + \varepsilon_i \qquad (4)$$

Where;

exp (ε_i) = a gamma-distributed error term with mean one and variance α.

X_i = vector of predictors such as geometric and traffic characteristics of roadway segment i that determine crash frequency

β = vector of estimable coefficients.

This leads to a conditional probability presented in Equation 5 as

$$P\ \ y_i\ \varepsilon\ \ = \frac{exp\ -\lambda_i\, exp\ \ \varepsilon_i\ \ \ [\lambda_i\, exp\ \ \varepsilon_i\ \ ]^{y_i}}{y_i} \qquad (5)$$

Integration of ε_i out of this expression produces the unconditional distribution of x_i. The formulation of this distribution is known as negative binomial (NB) which carries the following mathematical expression

$$P(y_i) = \frac{\Gamma(\theta+y_i)}{[\Gamma(\theta \cdot y_i!)]} \cdot \mu_i^{\theta} (1-\mu_i)^{y_i} \tag{6}$$

Where,

$$\mu_i = \frac{\theta}{\theta+\lambda_i}\ , \qquad \theta = \frac{1}{\alpha}.$$

The corresponding likelihood function is given by

$$L\ \lambda_i\ = \prod_{i=1}^{N} \frac{\Gamma(\theta+x_i)}{[\Gamma(\theta \cdot x_i!)]} \left(\frac{\theta}{\theta+\lambda_i}\right)^{\theta} \left(\frac{\lambda_i}{\theta+\lambda_i}\right)^{y_i} \tag{7}$$

Where

N is the total number of roadway segments.

Note that this model structure allows the mean to differ from the variance such that

$$\mathrm{Var}\ (x_i) = \lambda_i\ \ 1\ + \propto \lambda_i \tag{8}$$

Statistical significance of the estimated coefficient α (as measured by the t-statistic) is used to determine the choice between the negative binomial (NB) model and the Poisson model. If α is not significantly different from zero then Poisson regression modeling technique could be used. But, if α is significantly different from zero, the negative binomial is considered to be more appropriate.

2.3.1 Poisson and Negative Binomial Model Evaluation-Overdispersion Test

Selection of an appropriate method for analysis is influenced by several tests. As noted in the technical report (SAS, 1993), the common tests used by SAS software are

(1) deviance of a model *m* and

$$D^m = \ L^f\ + L^m \tag{9}$$

Where;

L^f= log-likelihood that would be achieved if the model gave a perfect fit
L^m = log-likelihood of the model
D^m = deviance

D^m is approximately to be chi-squared random variable with degrees of freedom equal to the number n of observations minus the number p of parameters. The test value Q is also developed which is deviance divided by degree of freedom. The model is overdispersed when Q is significantly larger than 1.i.e, Q > 1.

$$Q = \frac{D^m}{n-p} \qquad 10$$

(2) Pearson chi-square

Likewise, the Pearson chi-square statistic, defined by

$$X^2 = \sum_{i=1}^{n} \frac{(y_i - y_i)}{y_i} \qquad 11$$

Where;

X^2= Pearson chi-square
y_i =the estimated mean crashes
y_i=the observed crash in segment i

The test value Q is also developed which is Pearson chi-square divided by degree of freedom. The model is overdispersed when Q is significantly larger than 1. i.e. Q > 1.

$$Q = \frac{X^2}{n-p} \qquad 12$$

2.4 Existing Lane Width Crash Modification Factors

The Highway Safety Manual (HSM, 2010) provides a list of Crash Modification Factors (CMFs) for lane widths. The CMFs by HSM are from previous studies (e.g., Griffin & Mak, 1987; Zegeer *et al.*, 1988; Harwood *et al.*, 2000; Lord and Benneson, 2007; Harwood *et al.*, 2003). All of these studies were conducted on two-lane rural highways. CMFs from these studies are in the form of equations or constants. For instance, when considering CMFs for rural two-lane highways, the values of CMFs were expressed as constants. Separate CMFs were reported for AADT less than 400 motor vehicles per day and greater than 2000 motor vehicles per day. These CMFs indicate that widening of lanes reduced a specific set of related accident types, namely single-vehicle run-off-road accidents, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe collisions. This decrease was relative to 12 ft lane width, which was considered the base line of comparison. Figure 13 shows a graphical representation of these CMFs.

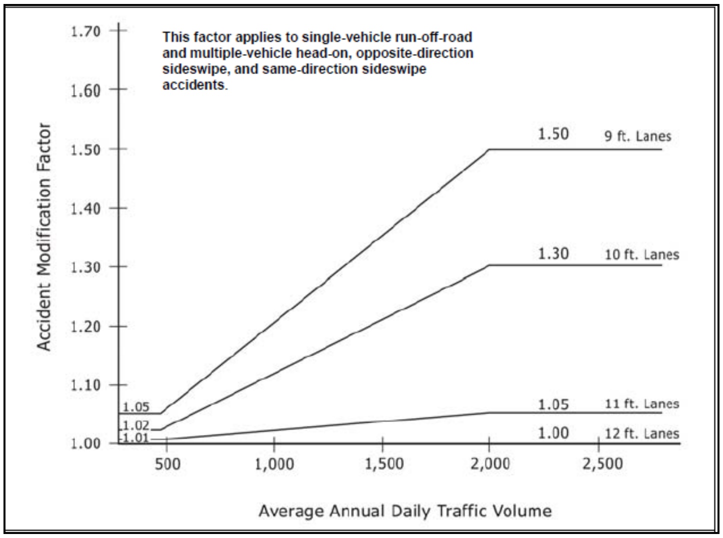

Figure 13 Potential crash effects of lane width on rural two-lane roads relative to 12 ft lanes (HSM, 2010)

CMFs reported in the Highway Safety Manual (2010) for rural multilane roadways were developed by the study that was conducted by the National Cooperative Highway Research Program (NCHRP Report 617, 2008). An expert panel was used to develop CMFs for rural multilane roadways. Lane width CMFs developed by modeling crashes for multi-lane highways are absent. Furthermore, it is clear that CMFs reported in HSM (2010) for rural multi-lane (both divided and undivided) highways may not apply to urban multi-lane roadways. This is due to the difference in traffic operations and level of activities surrounding urban highways

The lane width CMFs for undivided and divided rural multilane roadways are shown in Figures 14 and 15, respectively. When comparing the CMFs developed for two lane rural highways and undivided multilane rural highways, the effect of lane width on multilane was smaller than the effect of lane width on two-lane rural roadways. This effect was also observed in divided rural multilane highways.

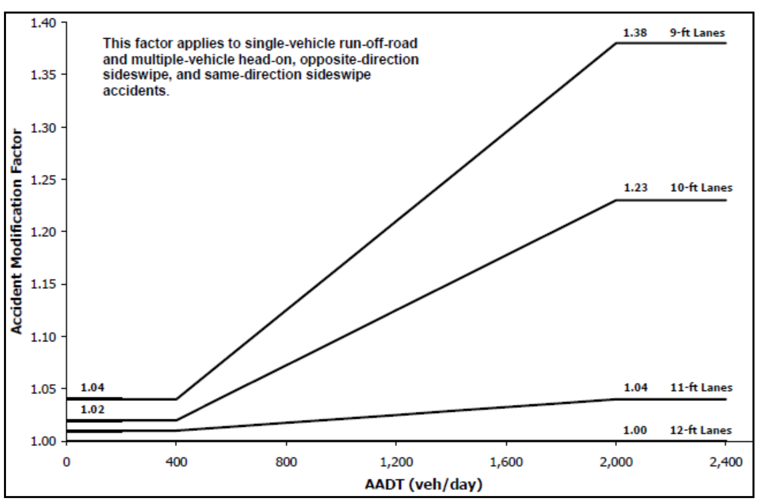

Figure 14 Potential crash effects of lane width on undivided rural multilane-lane roads relative to 12 ft lanes (HSM, 2010)

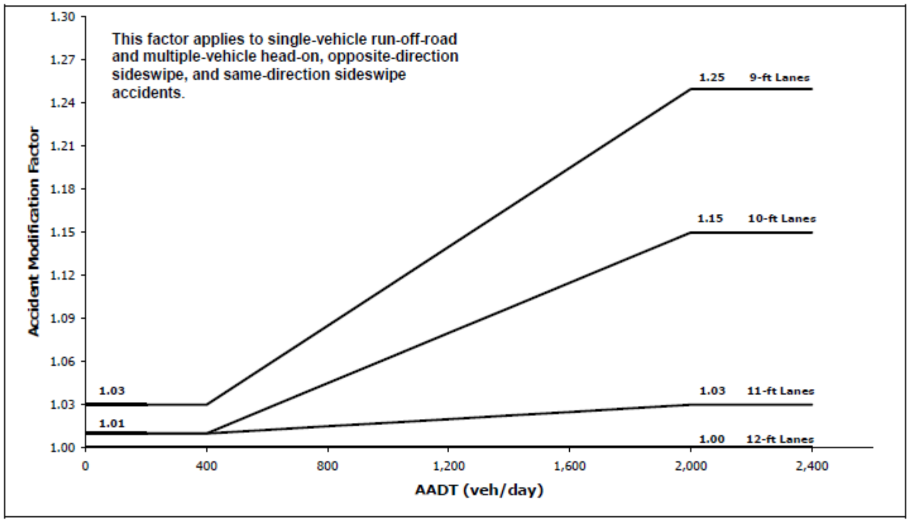

Figure 15 Potential crash effects of lane width on divided rural multilane roads relative to 12 ft lanes (HSM, 2010)

In another lane width study, Lord and Benneson (2007) developed lane width CMFs for two-lane rural highway frontage roads for the state of Texas. Rural frontage roadways differ from rural two-lane roadways because they have restricted access along at least one side of the road, a higher percentage of turning traffic, and periodic ramp-frontage-road terminals with yield control. The results showed increased crash frequency as lane width decreased from 12 ft to 9 ft.

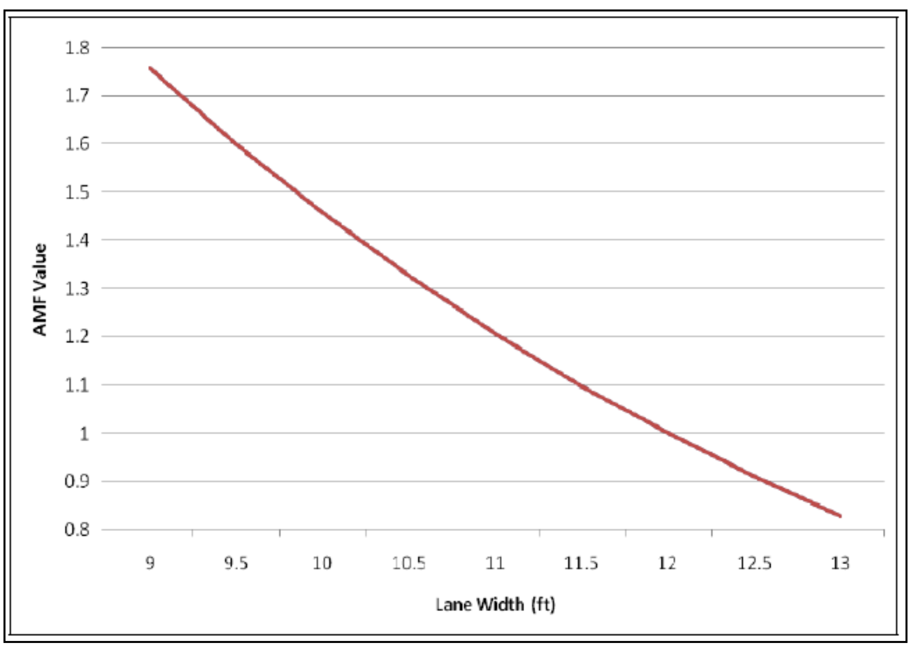

Figure 16 Potential crash effects of lane width on rural frontage roads (HSM, 2010)

In a recent lane width study, Potts *et al.* (2007) investigated the relationship between lane width and safety for roadway segments on urban and suburban arterials. The study by Potts *et al.* did not develop CMFs. The study did not find any indication of safety risk on urban and suburban arterials when lane width narrower than 12 ft was used.

2.5 Remarks

Based on the summary of the literature review, there are two main observations that need special attention. First, the average lane width was used in all previous studies that developed CMFs for lane width. While averaging may apply to symmetric lane configurations, such as 12 ft inside lane and 12 ft outside through lane, it may be too simplistic for asymmetric sections, which have wider outside through lanes and narrow inside lanes. Second, all existing CMFs for lane widths were developed for rural highways. None of the CMFs reported in previous studies were developed to specifically address the safety consequences of lane width in urban roadways. These two observations are the motivation of this study as it employs individual lane measurements instead of the average of aggregated lane width and focuses on urban segments, helping to fill the knowledge gap that exists in lane width CMF development.

CHAPTER 3. DATA COLLECTION

As explained earlier in this report (Chapter 1), the objective of this study was to develop CMFs for urban multilane roadways with asymmetric curb and gutter roads. Thus, the data collection process was first geared towards identifying locations with multilane roadway segments with asymmetrical lane width configuration.

It should be noted that the discussion on data collection presented in this chapter focuses on data needs for developing CMFs by using a cross-sectional method as described in the Highway Safety Manual (HSM, 2010). A discussion of the data collection process follows.

3.1 Data Collection Procedure

The first priority for this study was to find the locations of;

- asymmetric roadway segments (segments with 11 ft inside and wider outside through lane width) and
- comparison segments (segments with 12 ft inside and outside through lane widths)

FDOT's Roadway Characteristics Inventory (RCI) database does not record roadway surface width by lane; thus it was not possible to create a query for filtering the wide outside through lanes. The research team had to use other data collection strategies. In order to simplify the discussion on data collection, a flow chart of the procedure that was used is presented in Figure 17. The following sections give details on each of the steps presented in Figure 17.

3.2 Identifying Asymmetric Roadway Segments

Three sources were used for obtaining information on asymmetric roadway segments for this study. These sources are questionnaire surveys, National Household Travel Survey (NHTS), and FDOT inventory databases. Data collected from these three sources was summarized in an Excel spreadsheet. Attributes of interest included the road name, roadway identification number, county, town name, location, segment length, inside lane width, outside through lane width, speed, median width, beginning and end of mile post, maintaining agency, name of intersection street, lane configuration, street parking, number of driveways, and median type. The following sections provide details on each of the data sources.

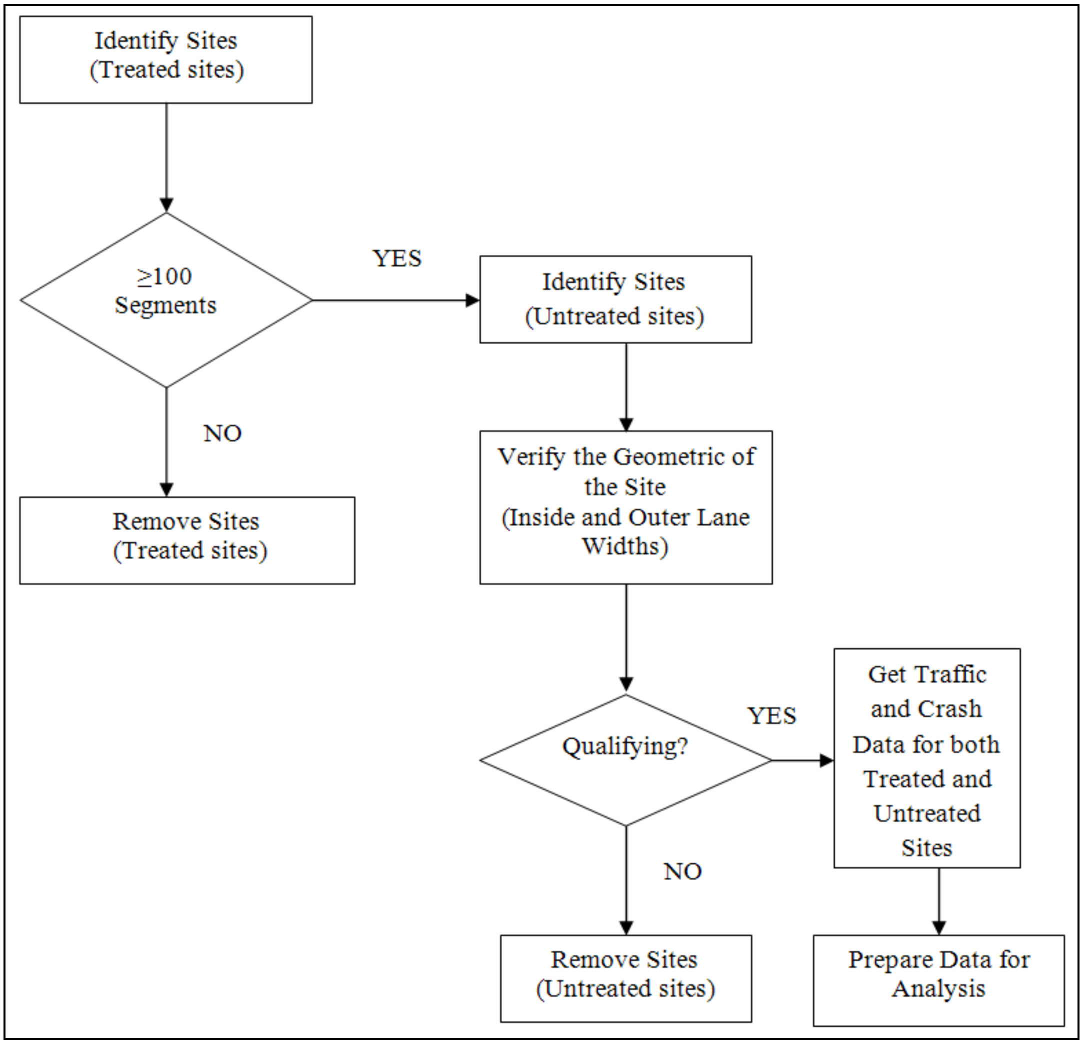

Figure 17 Flow chart of steps followed on data collection

3.2.1 Survey Questionnaire

Locations for data collection were chosen based on the availability of multilane roadway corridors with asymmetrical lane width configurations and potential number of bicycle riders. Bicycle and pedestrian coordinators from FDOT districts across the state of Florida were surveyed to provide information on the location of wide outside through lanes, with lane width greater than 12 ft but narrower than 14 ft.

A blank questionnaire is shown in Appendix A.1. The responses of the survey were recorded in either Excel spreadsheets or GIS shape files. All received data was sorted and only potential corridors for this study were retained for further analysis. To extend the analysis, the coordinators suggested that wide outside through lanes with lane widths wider than 14 ft be included in the study in order to analyze a greater range of lane widths.

3.2.2 Florida Department of Transportation Databases

At the beginning of the data collection, the research team considered using a number of resources that are maintained by FDOT. These resources included the RCI database, as-built plans, video logs, straight line diagrams, and the TRANSVIEW aerial mapping system. After a careful review of the capabilities and limitations of each resource, the research team decided to use the following FDOT resources.

3.2.2.1 Roadway Characteristics Inventory (RCI)

This database was used to identify the type of road configuration, geometrics of the segment (including an overall surface lane width), number of lanes, shoulder type, and traffic characteristics. Curbed roadway segments on suburban and urban areas were selected for further analysis. Appendix A.2 shows an image of the RCI Excel file. Segment configurations identified in RCI are as shown in Figure 18.

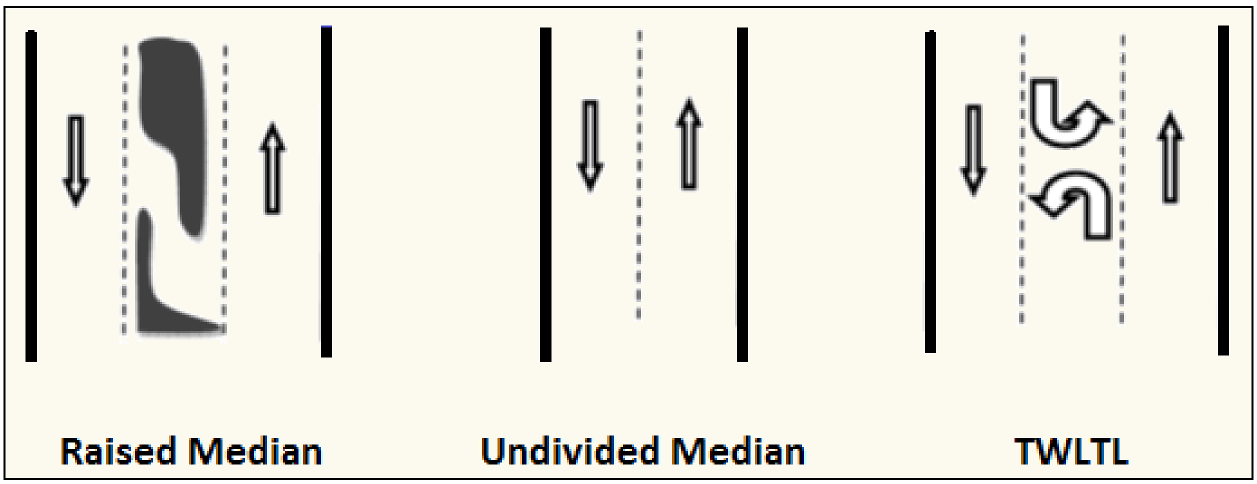

Figure 18 Segments configurations and characteristics

3.2.2.2 FDOT Scanned Copy of As-built Plans.

FDOT archives scanned copies of as-built plans for state maintained roadway projects. The as-built drawings are found in the FDOT construction intranet database. The database has most of the roadway plans for completed projects and projects that are under construction. From the as-built drawings, segment characteristics of roads identified from RCI are verified. This information, including individual lane widths, type of median, and approximated segment lengths, can be determined. The research team was able to utilize the capability of this database to extract a total of 426 asymmetric roadway segments of different lane configurations. The definition for mid-block segment was introduced as a portion of the road between two intersections and outside intersection zone of 250 ft radius. Figure 19 shows a mid-block segment. Appendix A.3 shows an image of an as-built plan drawing.

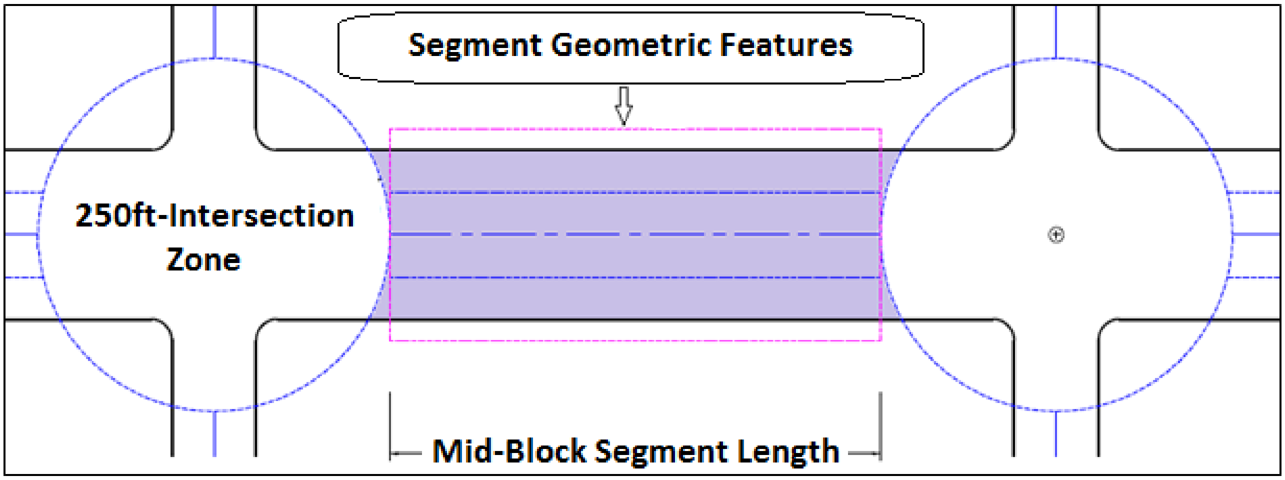

Figure 19 Mid-block segment as defined in this study

3.2.2.3 Straight Line Diagrams (SLDs).

FDOT districts maintain straight line diagrams (SLDs) for most of the state maintained roadways. These diagrams contain pertinent information such as intersection milepost, traffic control devices, averaged lane width, type of shoulder, number of lanes, and median widths. This project utilized the ability of SLDs to precisely provide the milepost of each intersection, to determine the lengths of individual segments. Appendix A.4 shows an image of a SLD drawing.

3.2.2.4 National Household Travel Survey (NHTS) and Transportation Analysis Zone (TAZ) Data.

The National Household Travel Survey (NHTS 2009) data were merged with the Transportation Analysis Zone (TAZ) data to determine the active level of bicyclists in different location with roads with asymmetrical lane width configuration. The bike trips origin and destination information were filtered from NHTS database for different Florida counties. The filtered information was then merged with TAZ information for the corresponding counties. TAZ are geographic zonal layers used in travel demand forecasting to predict daily and peak hour motor vehicle trips on roadway networks. Most are available in the Florida Geographic Data Library (FGDL) in GIS format, but can also be requested from city transportation planning offices.

The merged information was converted to GIS maps for visualization. Shape files for asymmetrical lane width configuration roadways were developed and appended on top of the GIS map, using thicker lines. Using the GIS map, bicyclist activity levels close to asymmetrical lane width configuration roadways were determined. An assumed conservative cutoff line for bicyclist activity level was based on the number of bicyclist commuters observed on the TAZ close to asymmetrical lane width configuration.

All asymmetrical lane width configuration segments that appeared to be in an area where the numbers of bicyclist commuters was less than five were excluded as the bicyclists' risk of exposure to accident was assumed to be relatively low.

Figure 20 shows an example of asymmetrical lane width configuration roads within different TAZs and their corresponding number of bicyclist commuters. Thick blue lines on the map represent streets with asymmetrical lane width configuration roadways.

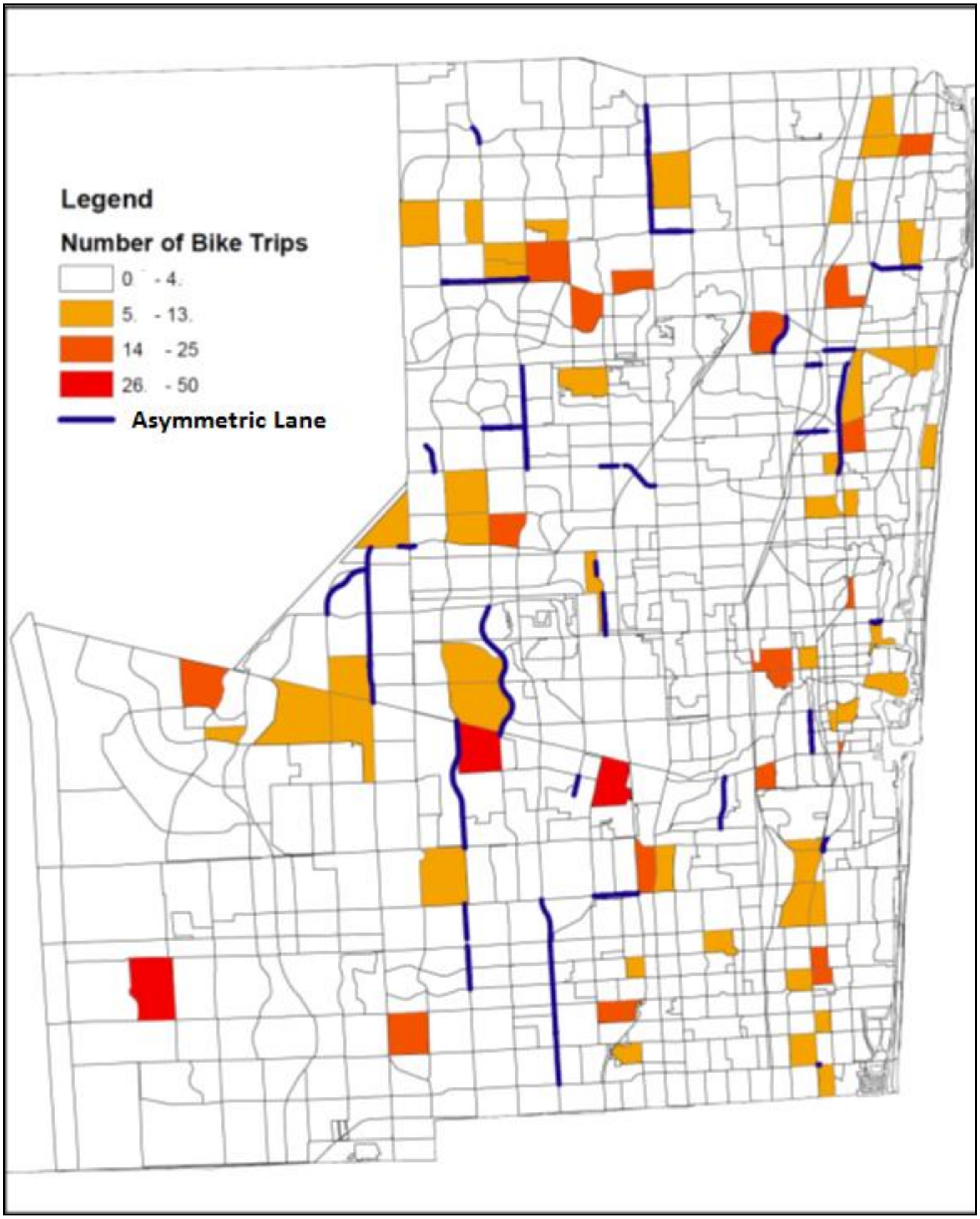

Figure 20 GIS map of Broward County: asymmetrical lane width configuration roads within different TAZ's and their corresponding number of bicyclist commuters

Table 12 shows a summary of the amount of asymmetric roadway segments that were extracted for each lane configuration. About 45.94% of asymmetric roadway corridors were 4-lanes divided (4D) while 4.29% were undivided (4U) roads. Approximately 33.69% were found to have a two-way left-turn lane (TWLTL) median (5T).

Asymmetric roadway Six-lane segments (6D, 6U, and 7T combined) were less than 20% of total segments as shown in Table 12. There were no 8-lane asymmetric roadway corridors for both divided (8D) and undivided (8U) roadways.

Table 12 Summary of Asymmetric Roadway Segment Miles and Number of Segments

Lane configuration	Total miles	Number of segments	Segment Percentage
6U	1.06	7	1.07%
7T	2.27	11	1.68%
4U	3.58	28	4.29%
6D	16.87	87	13.32%
5T	33.04	220	33.69%
4D	43.51	300	45.94%
Total	**100.33**	**653**	**100.00%**

3.3 Identification of Comparison Segments

As most of the segments were expected to have zero crashes, the issue of sample size became a paramount concern. A minimum criterion of 100 segments was selected as a cutoff point. According to Agrawal and Lord (2006), 100 segments are considered a sufficient sample size for regression analysis. For asymmetric roadway segments, lane configurations other than 4D and 5T had less than 100 segments (Table 12). For this reason, only 4D (300 segments) and 5T (220 segments) asymmetric roadway segments were considered for further analysis.

Since only 4D and 5T asymmetric roadway segments were considered for analysis, only 4D and 5T comparison sites were searched. The criteria for selection are shown above in Figures 21 to 23. Adjacent segments on the same roadway were selected to ensure that the pairs were as nearly matched as possible, as suggested by Bonneson & Pratt (2009). However, the research team later realized the difficulty in getting enough information using this technique. Therefore, it was decided to expand the selection by considering segments in streets that were parallel or perpendicular to the asymmetric roadway segments. Intersecting segments were considered for inclusion as long as their ADTs and number of bicyclist commuters were considerably similar to asymmetric roadway segments and attributes of segments, except lane width, were identical to the asymmetric roadway segments. Comparison segments for this case were roadways with standard lane widths of 12 ft for both inside and outside through lanes.

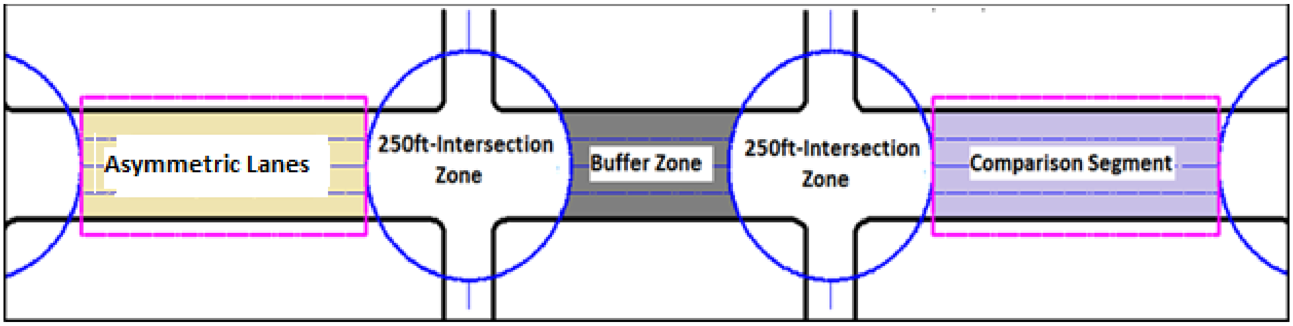

Figure 21 Criteria used in selection of comparison segments

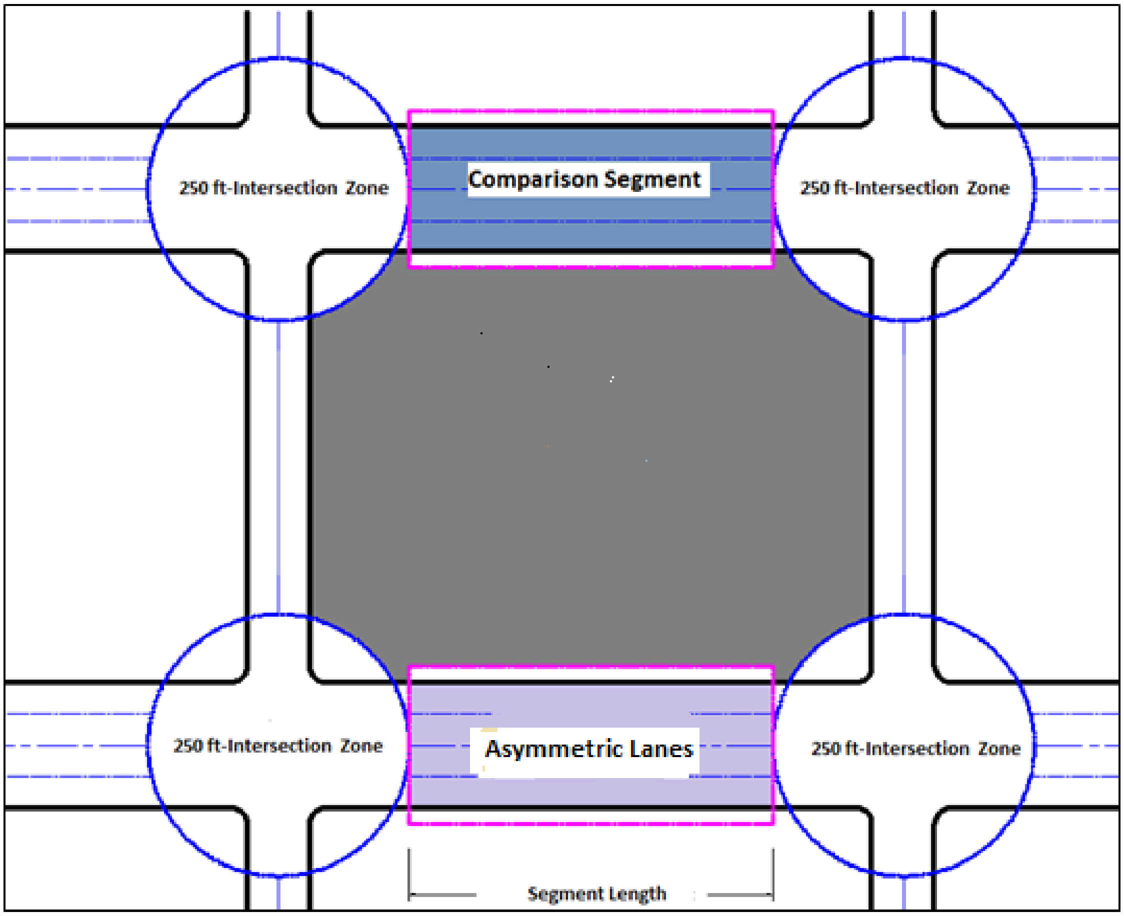

Figure 22 Criteria used in selection of comparison segments

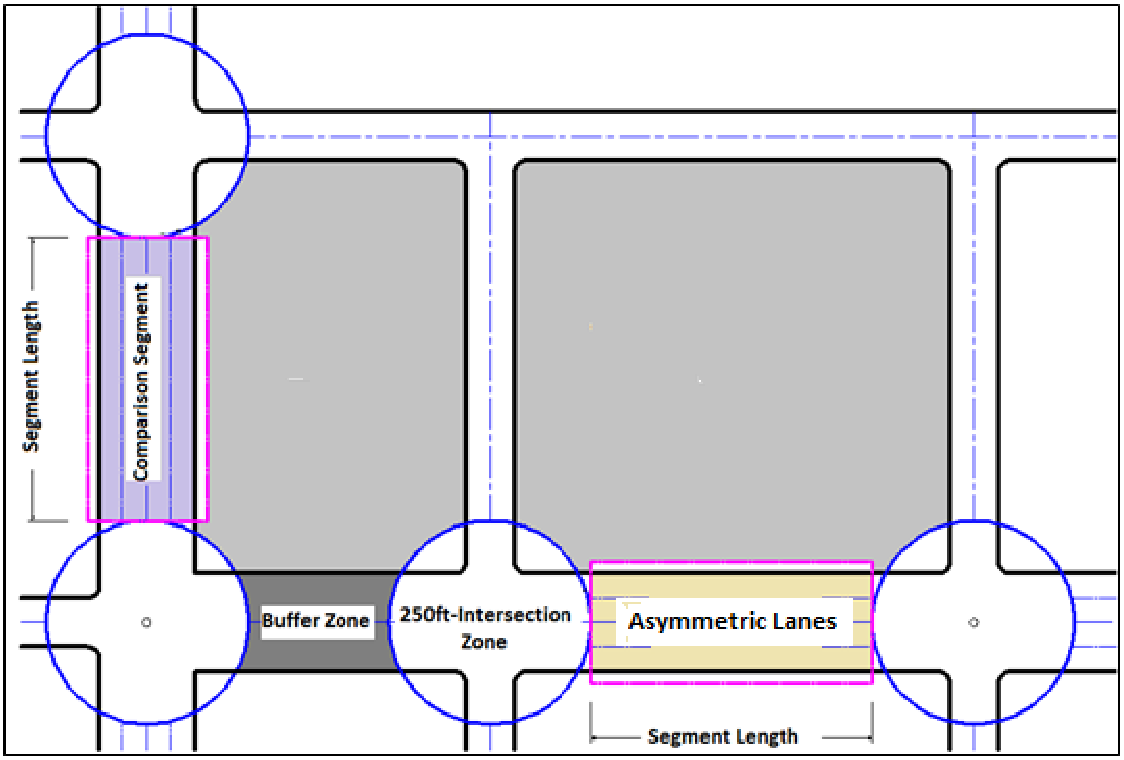

Figure 23 Criteria used in selection of comparison segments

3.4 Verification of Roadway Geometric Information for Asymmetric Roadway and Comparison Roadway Segments

Two issues emerged when reviewing the as-built drawings. First, it was discovered that most as-built plans are not updated regularly. Second, there was inconsistency in the way the outside through lane was measured. Therefore, measurements from as-built plans were verified by performing field measurements for asymmetric roadway segments and comparison segments. A total of 918 roadway segments were verified. The verification exercise encompassed all regions of the state. About half the segments were dropped after field verification, since the field measurements did not match the measurements recorded on the as-built drawings. However, after verification, both 4D and 5T were found to have enough segments for both asymmetrical lane width configuration and comparison segments with a total of 224 and 240 segments respectively.

3.5 Merging Segments with Crashes

Statewide crash data was obtained from Florida Department of Transportation Crash Analysis Report (CAR) database. Crash history ranging from year 2004 to 2009 was retrieved from CAR database. Two files of crash information, the short and the augmented files, were downloaded as text files and converted to Excel files. The two files were merged using Microsoft Access software with the crash reporting number as a key identifier.

Using the merged file, the locations of crashes were linearly referenced to the FDOT roadway system using the milepost system in Exel by the roadway identification number (Roadway ID).

Crash data were screened to remove crashes that occurred at intersections – only mid-block crashes were retained. It is important to mention that after filtering out intersection crashes, scanned crash reports were examined to verify that all crashes used in the analysis were not intersection related.

CHAPTER 4. DATA ANALYSIS

This chapter is divided in three sections (1) explanatory analysis of the data used for crash modeling, (2) development of Safety Performance Functions (SPFs), and (3) development of Crash Modification Factors (CMFs).

The first section has three subsections which analyze and summarize the data collected in chapter 3. The second section contains six subsections, and the last has a total of four subsections. The subsections in the last two sections describe the methodological approach used in the modeling of crashes as well as the results obtained.

4.1 Explanatory Analysis of Collected Data

Two types of data have been used in this section. The first set of data was extracted from segment geometrics which included segment lengths as well as outside through lane width. The second set of data was based on crashes recorded from individual segments. The data was grouped in terms of severity extent, i.e. injuries, fatalities, or property damage only. Using these two main types of data, three explanatory analyses were conducted; a detailed explanation of the analysis follows.

4.2 Analysis of Geometrics of Segment Data

Explanatory data analysis was conducted on two types of roadway. These roadways were

- four-lane roadways (two lanes each direction) with a raised divided median (4D) and
- four-lane roadways with a two-way left-turn lane (5T)

Both asymmetric roadway segments (segments with 11 ft inside and wider outside through lane width) and comparison segments (segments with 12 ft inside and outside through lane widths) were analyzed. Segment lengths and outside through lane widths were categorized in ranges/bins describing their upper and lower limits. Total miles and number of segments bound in each bin were computed. Summaries are provided in Tables 13 and 14.

Table 13 below shows that almost a quarter of 4D segments were found in the range between 0.05 miles and 0.10 miles. The shortest segment length was found to be 0.01 miles while the longest was 0.64 mile. As shown in Table 14, it was also observed that more than half of 5T total segments ranged between 0.05 miles and 0.10 miles. The shortest segment length was found to be 0.01 miles while the longest was 0.52 miles. Considering data from both tables, it is evident that most segments were shorter than 1 mile in length.

Regarding outside through lane widths, Table 13 shows that the most dominant outside through lane width for 4D ranged from 13.3 ft and 13.7 ft, with a class mark of 13.5 ft. The same was observed for 5T segments as depicted in Table 14.

Table 13 Distribution of Road Segment Miles and Number of Segments - 4D

Selected Roadway Segments with 11 ft Width for Inside Lane and Varying Outside through lane Width

	Range(mi)	Total Miles	Segments		Range (ft)	Total Miles	Segments
Segment Length	.01 - .05	0.51	14	Outside Lane Width	11.8 - 12.2	0	0
	.05 - .10	1.96	28		12.3 - 12.7	5.55	36
	.10 - .15	2.17	17		12.8 - 13.2	11.34	58
	.15 - .20	2.3	13		13.3 - 13.7	0.89	6
	.20 - .25	3.89	17		13.8 - 14.2	1.55	12
	.25 - .30	2.84	10				
	>.30	5.67	13				
	TOTAL	19.33	112		TOTAL	19.33	112

Comparison Roadway with 12 ft Lane Widths for both Inside and Outside Lane by Miles and Number of Segments

	Range(mi)	Total Miles	Segments		Range (ft)	Total Miles	Segments
Segment Length (mi)	.01 - .05	0.37	10	Outside Lane Width (ft)	12 ft for All Segments	The Same as for Segment Length Distribution	Total of 112 Segments
	.05 - .10	2.86	34				
	.10 - .15	2.5	19				
	.15 - .20	2.73	15				
	.20 - .25	3.52	15				
	.25 - .30	1.4	5				
	>.30	5.95	14				
	TOTAL	19.33	112				

Table 14 Distribution of Road Segment Miles and Number of Segments - 5T

Selected Roadway Segments with 11 ft Width for Inside Lane and Varying Outside Lane Width

	Range(mi)	Total Miles	Segments		Range (ft)	Total Miles	Segments
Segment Length	.01 - .05	0.24	7	Outside Lane Width	11.8 - 12.2	0	0
	.05 - .10	4.4	64		12.3 - 12.7	2.62	20
	.10 - .15	3.42	30		12.8 - 13.2	3.57	33
	.15 - .20	1.19	7		13.3 - 13.7	4.55	52
	.20 - .25	1.37	6		13.8 - 14.2	1.83	15
	.25 - .30	0.78	3				
	>.30	1.17	3				
	TOTAL	12.57	120		TOTAL	12.57	120

Comparison Roadway Segments with 12 ft Lane Widths for both Inside and Outside Lane by Miles and Number of Segments

	Range*	Miles	Segments		Range	Miles	Segments
Segment Length	.01 - .05	0.33	9	Outside Lane Width	12 ft for All Segments	The Same as for Segment Length Distribution	Total of 120 Segments
	.05 - .10	4.1	60				
	.10 - .15	3.92	32				
	.15 - .20	1.45	9				
	.20 - .25	0.63	3				
	.25 - .30	1.61	6				
	>.30	0.34	1				
	TOTAL	12.38	120				

4.3 Analysis of Crash Severities

Crash severities for four-lane roadways with a raised divided median (4D) and four-lane roads with a two-way left-turn lane (TWLTL) type median (5T) were collectively analyzed and categorized into four main groups: (1) fatal crashes, (2) incapacitating injury crashes, (3) possible and non-incapacitate injury crashes, and (4) property damaged only (PDO) crashes. Because fatal crashes and incapacitating injury crashes had the lowest frequency, the two groups were merged to form a single group, which reduced the groups from four to three.

Crash percentages for individual groups were then computed for both asymmetric roadway segments and comparison segments. Histogram plots (Figure 24 and 25) were generated to provide visual comparison of the crashes for each crash group. When considering 4D roads, found in Figure 24, percentage crashes from all three groups were approximately the same for both asymmetrical lane width configuration and comparison segments. However, for 5T roadways, property damage only (PDO) crashes for comparison segments dominated, and possible and non-incapacitate injury crashes favored asymmetrical lane width configuration segments, as shown in Figure 25.

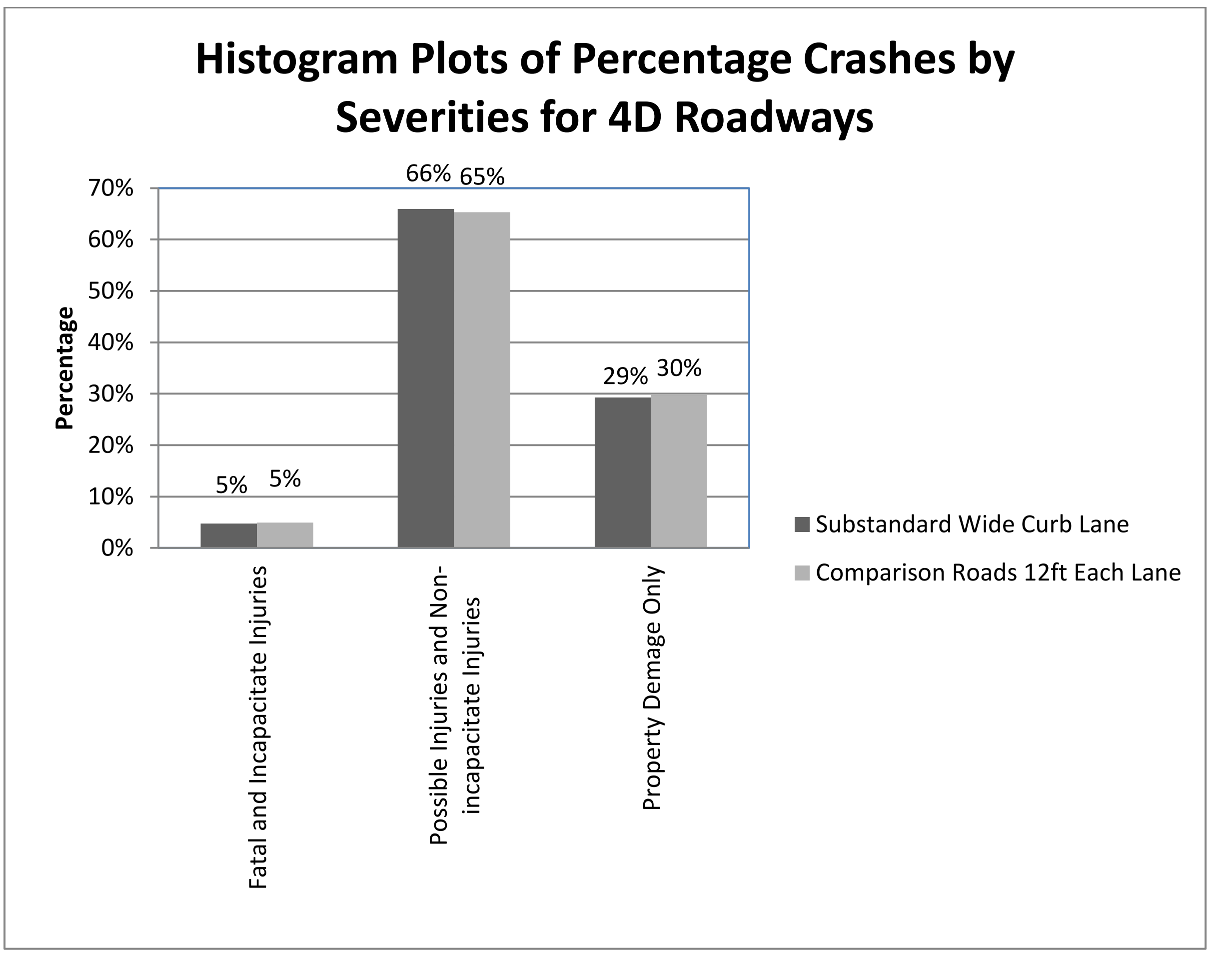

Figure 24 Histogram plots of percentage crashes by severities

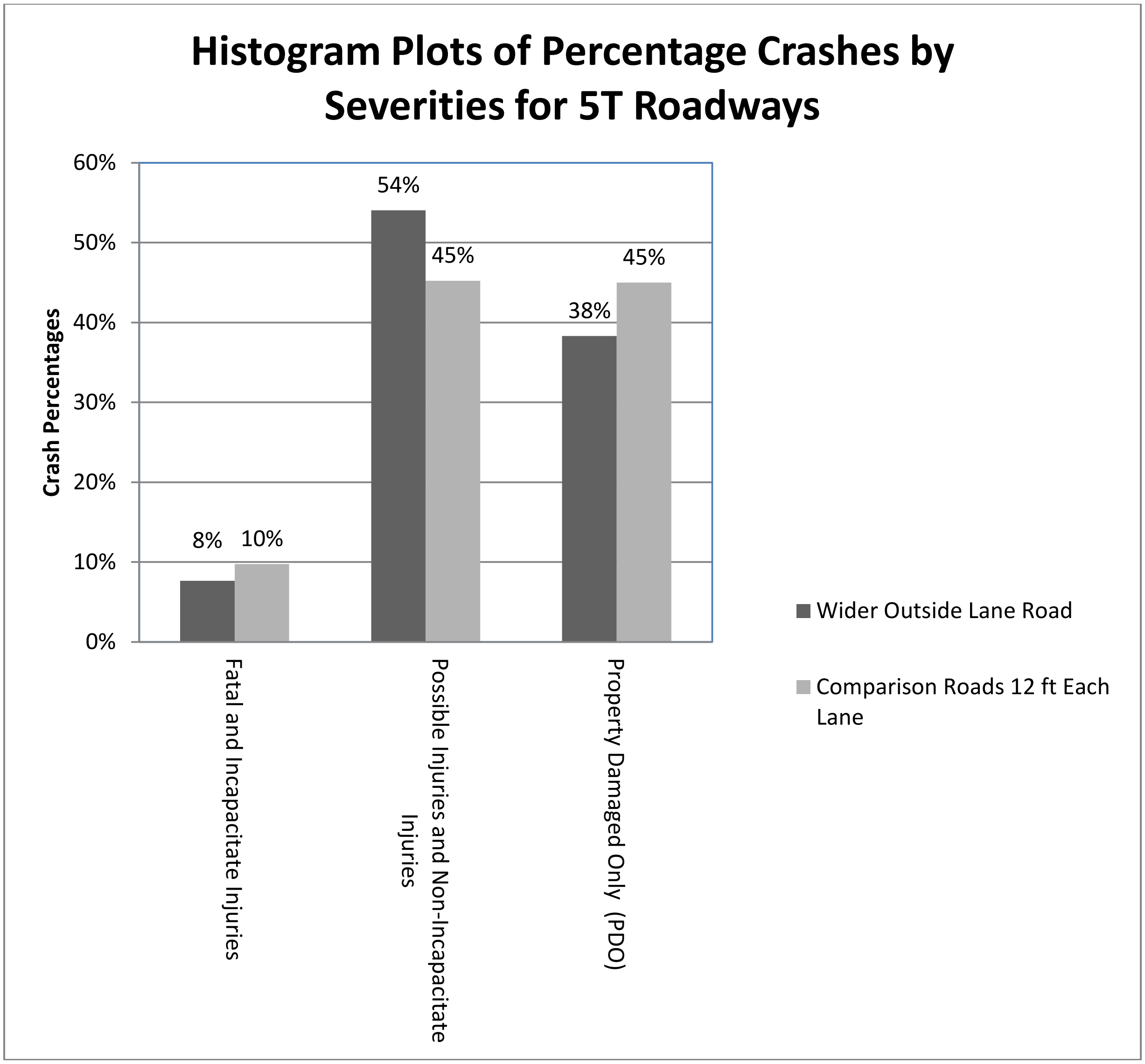

Figure 25 Histogram plots of percentage crashes by severities

For both 4D and 5T configurations, the three crash groups were reduced to form two main groups. These groups are; (1) KABC i.e. {Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), possible injury (C) crashes} and (2) Property damage only crashes abbreviated as PDO. In addition, another group of crashes abbreviated as (KABCO) i.e. {Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), possible injury (C) and PDO (O) crashes} was also introduced which is the sum of PDO and KABC crashes. Explanatory analysis of the two groups was enacted and the results are summarized in Table 16 and 17.

Table 15 Crash Severity Terminology

KABCO	Fatal (K), incapacitating (A), non-incapacitating (B), possible injury (C) and PDO (O) crashes
KABC	Fatal (K), incapacitating (A), non-incapacitating (B), and possible injury (C) crashes
PDO	Property damaged only

Table 16 Crash Rate for Different Types of Crash Severities 4D Roads

Variable			KABCO[1] Crashes [KABC[2] Crashes] (PDO[3] Crashes)	
			Asymmetrical Lane[4] Width Configuration	Comparison[5] Segments
Sum of Segment Length (mile)			19.33	19.33
Number of Segments			112	112
Crashes in 6 Years (2004 to 2009)	Per segment	Average	7.13 [4.18] (2.95)	6.60 [3.8] 2.79
		Minimum	0 [0] 0	0 [0] 0
		Maximum	57 [34] (28)	66 [32] (34)
	All segments	Sum	798 [468] (330)	739 [426] (313)
		Crash Rate (crashes/mvm)[6]	0.49 [0.29] (0.20)	0.45 [0.26] (0.19)

1. KABCO- All 5 Severity Crash Levels (Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), minor injury, (C) and property damage only (O) crashes

2. Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), and minor injury, (C) crashes

3. Property Damage Only (PDO)

4. Asymmetric segments have narrower inside lane and wider outside through lane width

5. Comparison segments are roadways with standard lane widths of 12 ft for both inside and outside through lanes

6. Crash rate has units of yearly crashes per million motor vehicle miles (crashes/mvm)

As shown in Table 16, for 4D segments, the highest value of KABCO, KABC and PDO crashes per segment were observed on asymmetrical lane width configuration segments with an average of 7.13, 4.18, and 2.9 crashes per segment. For the same types of crash severities, the asymmetric roadway segments, the highest average crash rate of 0.49, 0.29 and 0.20 crashes/million motor vehicle miles were observed.

Descriptive statistics for 5T segments are summarized in Table 17. For the 5T configuration, the average of 2.42 crashes/segment and maximum of 26 crashes/segment were observed in asymmetric roadway segments. The comparison segments for the same configuration had an average of 1.93 crashes/segment and maximum of 18 crashes/segment. Comparison sites were found to have higher values for PDO crashes, with an average of 1.58 crashes/segment and maximum 20 crashes/segment whereas asymmetric roadway segments were found to have an average of 1.50 and maximum of 19 crashes/segment. For both KABC and PDO, a minimum of 0 crash/segment was observed for both asymmetric roadway segments and comparison segments.

Table 17 Crash Rate for Different Types of Crash Severities 5T Roadways

Variable			KABCO[1] Crashes [KABC[2] Crashes] (PDO[3] Crashes)	
			Asymmetrical Lane Width[4] Configuration	**Comparison Roads[5]**
Sum of Segment Length (mile)			12.57	12.38
Number of Segments			120	120
Crashes in 6 Years (2004 to 2009)	Per segment	Average	3.92 [2.42] (1.5)	3.50 [1.93] (1.58)
		Minimum	0 [0] (0)	0 [0] (0)
		Maximum	32 [26] (19)	34 [18] (20)
	All segments	Sum	470 [290] (180)	420 [231] (189)
		Crash Rate (crashes/mvm)[6]	0.70 [0.43] (0.27)	0.66 [0.36] (0.30)

1.KABCO- All 5 Severity Crash Levels (Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), minor injury, (C) and property damage only (O) crashes

2. Fatal (K), incapacitating-injury (A), non-incapacitating injury (B), and minor injury, (C) crashes

3. Property Damage Only (PDO)

4. Asymmetric segments have narrower inside lane and wider outside through lane width

5. Comparison segments are roadways with standard lane widths of 12 ft for both inside and outside through lanes

6. Crash rate has units of yearly crashes per million motor vehicle miles (crashes/mvm)

4.4 Crash Rate Analysis for Asymmetric Roadway Segments

Explanatory analysis for different lane width categories was conducted to determine whether a relationship existed between crash rates and outside through lane widths. This analysis was for both 4D and 5T configurations.

For 4D, class marks were computed for each outside through lane widths' ranges/bins range reported in Table 13. Lane width categories were as follow: (11.8 - 12.2) ft formed a 12 ft category, (12.3 – 12.7) ft formed a 12.5 ft category, (12.8 – 13.2) ft formed a 13 ft category, (13.3 – 13.7)ft formed a 13.5 ft category, and (13.8 – 14.2) ft formed a 14 ft category. The values obtained were used to create outside through lane width for analysis reported in Table 18 and 19.

For the 12 ft category of outside through lane width, the inside lane width was 12 ft as well. However, for the remaining outside through lane width categories, the inside lane widths were fixed to 11 ft. Exposures (E) were computed on each lane width category. The formula used to compute exposure is shown below:

$$E = \frac{(ADT\ x\ \ L\ x\ Y\ x\ 365)}{1{,}000{,}000} \tag{13}$$

Where;

E = Exposure in million motor vehicle miles (MVM)
ADT= Average Daily Traffic for segment i in (motor vehicle per day)
Y=Total number of years the data was collected for segment i
L=Length of the individual segment i in miles

The sums of KABCO, PDO and KABC for each lane width category were divided by the total exposure (E) for that category to obtain crash rate. The resulted lane width categories with their corresponding crash rate are reported in Table 18 and 19.

Table 18 Crash Rate for Different 4D Outside through lane Width Categories

Inside Lane Width	Outside Lane Width	Exposure (mvm)	KABCO Crashes	PDO Crashes	KABC Crashes	KABCO Crashes/mvm	PDO Crashes/mvm	KABC Crashes/mvm
12	***12.0**	1631.24	739	313	426	0.45	0.19	0.26
11	12.5	297.81	219	84	135	0.74	0.28	0.45
11	13.0	595.56	372	164	208	0.62	0.28	0.35
11	13.5	482.45	162	63	99	0.34	0.13	0.21
11	14.0	254.45	45	19	26	0.18	0.07	0.10

***12.0:** *Implies inside lane width is 12.0 ft.*

Table 19 Crash Rate for Different 5T Outside through lane Width Categories

Inside Lane Width	Outside Lane Width	Exposure (mvm)	KABCO Crashes	PDO Crashes	KABC Crashes	KABCO Crashes/mvm	PDO Crashes/mvm	KABC Crashes/mvm
12	***12.0**	634.31	420	189	231	0.66	0.30	0.36
11	12.5	215.94	187	79	108	0.87	0.37	0.50
11	13.0	209.46	153	56	97	0.73	0.27	0.46
11	13.5	88.16	59	21	38	0.67	0.24	0.43
11	14.0	120.84	71	24	47	0.59	0.20	0.39

***12.0:** *Implies inside lane width is 12.0 ft.*

Figures 26 and 27 are graphical representations of the results shown in Tables 18 and 19, depicting the relationship between crash rate per million vehicle miles (mvm) and the outside through lane width. The two graphs presented in Figures 26 and 27 show an increase of crashes when outside through lane width increased from 12 ft (with inside lane width of 12 ft) to 12.5 ft (with an inside lane of 11 ft). There is a discernible pattern of decreased crash rate as the outside through lane width is increased from 12.5 ft to 14 ft with a fixed inside lane width of 11 ft. This trend was observed for all three crash categories, i.e., KABCO, KABC, and PDO KABC crashes.

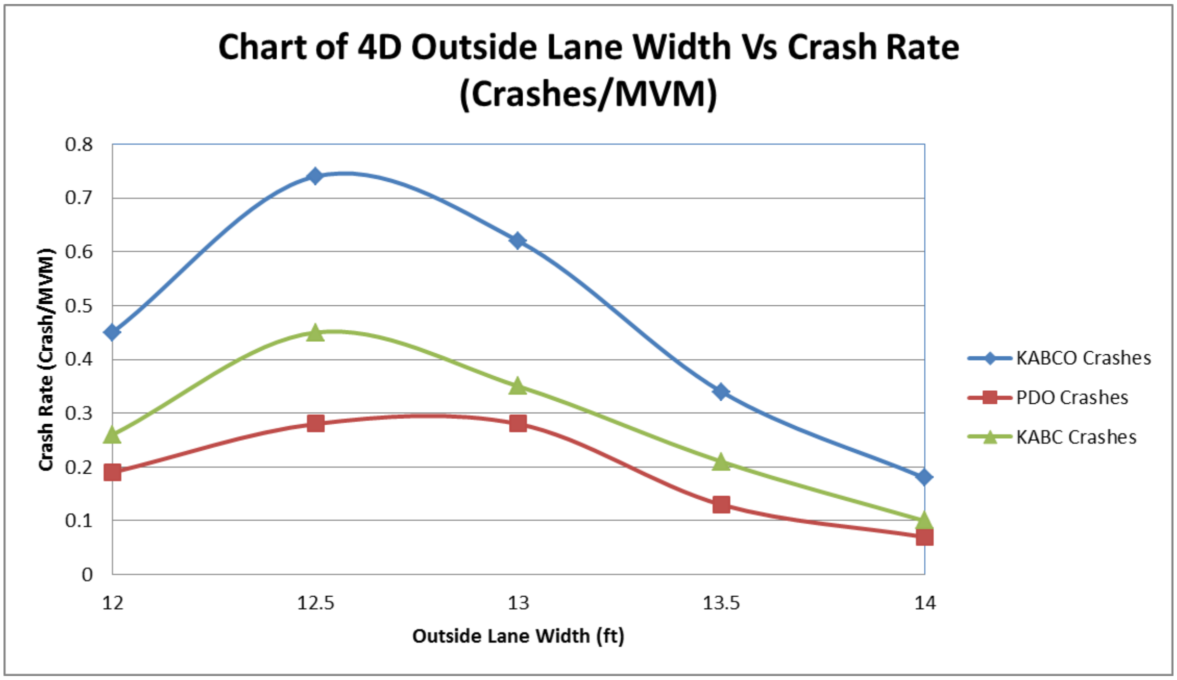

Figure 26 4D-Graphs for outside through lane width and crash rate by severities

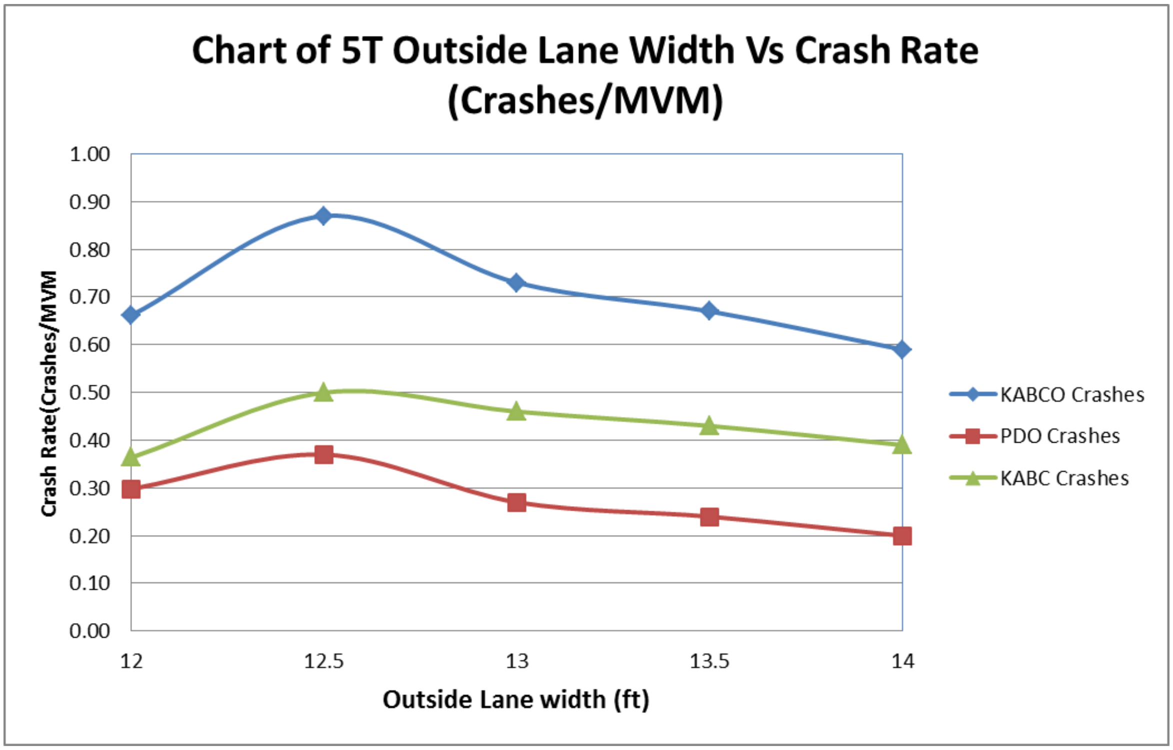

Figure 27 5T-Graphs for outside through lane width and crash rate by severities

4.5 Developing Safety Performance Functions

Roadway crashes are discrete and randomly distributed in nature, forcing researchers to rely on the use of stochastic regression models, such as the Poisson method or negative binomial method, to develop prediction models. These models are famously known as Safety Performance Functions (SPFs). Safety Performance Functions (SPFs) are regression models that have been developed for specific site types and base conditions, the specific roadway and traffic control features of a base site. In most cases, SPFs are a function of few variables, primarily AADT and segment length. In the Highway Safety Manual (2010), SPFs are used as predictive models to estimate the predicted average crash frequency for a particular site type.

4.5.1 Selection of the Function

The first step toward development of predictive models is the selection of the functional form. Normally, the function is determined empirically after several runs of different variable combinations, which correlate the dependent variable (outcome variable) to the covariates of the model. Different functions were considered and fitness of resulting models assessed. After several trials of different combination of variables, the function form based on negative binomial (NB) model, shown below as Equation 14, was selected.

$$\mu_i = \beta_o L_i (ADT)^{\beta_1} e^{\sum_{i=2}^{n} x_{ji}\beta_i} \qquad (14)$$

Equation 14 was simplified to provide linear relationship between the dependent variable and covariates by taking natural logarithm on both sides. The resulting formula is presented as Equation 15.

$$\ln(\mu_i) = \ln\ \beta_o\ + \ln\ L_i\ + \beta_1 \ln\ ADT\ + \sum_{i=2}^{n} x_{ji}\beta_i \qquad (15)$$

Where

ADT=is an average daily traffic over six years of study period
L_i= segment length
μ_i=mean number of crashes for six year period for site i
$x_1, x_2, \ldots\ldots x_n$= explanatory variables
$\beta_o, \beta_i, \ldots\ldots, \beta_n$ = regression coefficient to be estimated

4.5.2 Selection of Explanatory Variables

The literature review revealed that roadway cross-section variables such as lane width, median width, median type, grade, segment length, and degree of curve have contributed to occurrences of crashes (Zeeger *et al.*, 1987; Goldstine, 1991; HSM, 2010). Also, Mauga and Kaseko (2010) found that median opening density and driveway density contribute to the increase in crashes in urban multilane roadways.

In addition, previous studies have mentioned traffic variables such as ADT as contributing to crashes (Lord and Bonneson, 2007; Mauga and Kaseko, 2010; HSM, 2010). In this study, two main explanatory variables – ADT and segment length – were considered key variables that relate number of crashes to predictors. In addition, inside and outside through lane width were considered study variables and given equal importance as key variables. Due to the nature of 5T configurations, other variables that affected selection of function were: median (TWLTL) width (ft), degree of curve (degree) and driveway density (number of driveway/ 0.1 mile). Number of median opening density was found to be irrelevant for 5T segments as the configuration does not restrict turning at any point. However, median opening density was relevant for 4D configuration since turning to access adjacent properties is permitted at specific locations with a median opening.

In previous studies, driveway density and median opening density have been expressed in terms of number of driveways/mile or number of openings/mile. However, for this study, segment lengths ranged from 0.01 miles to 0.52 miles for 5T configurations, 0.1 mile being the mean value. To avoid having large values for driveway density and median openings, the mean segment length of 0.1 miles was used to scale the median openings and driveway density; this is why the number of driveways are presented per 0.1 mile.

4.5.3 Descriptive Analysis of Selected Modeling Variables

Two separate data groups, asymmetrical lane width configuration segments and comparison segments, described in the previous chapter (Chapter 3) were combined. A third and fourth database, with 420 segments for 4D and 240 for 5T configurations, were formed. Thirty eight 4D and thirty four 5T segments with posted speed limits above 45 mph were removed, limiting analysis to low speed roadways.

Tables 20 and 21, show the descriptive statistics of the explanatory variables for the 206 remaining 5T and 382 4D segments used to determine the SPFs. All variables used in this study were continuous variables.

Table 20 5T-Metadata for the KABC, PDO and KABCO Crashes

Variable	Mean	Standard Deviation	Minimum	Maximum
ADT	22078	7118	7480	43929
Segment length (length)	0.10	0.07	0.01	0.52
Outside through lane width (ft)	12.6	0.70	12.0	14.0
Inside Lane width (ft)	11.5	0.50	11.0	12.0
Median Width (ft)	12.1	1.0	10.0	14.0
Drive way density (drive way/0.1mile)	5	3	0	24

Table 21 4D-Metadata for the KABC, PDO and KABCO Crashes

Variable	Mean	Standard Deviation	Minimum	Maximum
ADT	37510.30	7383.39	25100	52500
Segment length (length)	0.17	0.12	0.01	0.64
Outside through lane width (ft)	12.63	0.71	12	14
Inside Lane width (ft)	11.68	0.36	11	12
Median opening density	0.68	1.30	0	10.6
Drive way density (drive way/0.1mile)	1.16	2.07	0	19

4.5.4 Negative Binomial (NB) Model Selection and Evaluation

Using a built-in procedure in SAS software known as GENMOD, Equation 15 was used to model variables. Multiple runs were performed using Poisson distribution with the *log link* function. Tests on the resulting model were performed to determine the existence of an over-dispersion. The presence of an over-dispersion indicates that the Poisson assumption of equal mean and variance, based on the model data does not apply.

After reviewing the Wald 95% confidence limit, an over-dispersion was observed. Thus the decision was made to switch to the negative binomial model which accounts for over-dispersion.

The NB model was developed to analyze the influence of the independent variables (shown in Tables 22 and 23) on three response variables: all severity levels (KABCO), fatalities, incapacitating and minor injuries (KABC) and property damage only (PDO). For all three responses, a full model with all variables was completed. Model results were tested at 0.05 and 0.10 levels of significance. All insignificant variables were removed from the two tested levels to form a reduced model. A reduced model was completed and tested again at the same levels of significance. Thereafter, a comparison of the models was performed using two information-theoretic approach indicators, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The general criterion for comparison is the model with smaller values of AIC and BIC; it serves as a more appropriate model than the model with higher values.

The full and reduced models were compared in order to select the optimal model. The KABCO, KABC, and PDO results for the values of BIC and AIC were higher for the full model than those of the reduced models. Hence, the models with fewer parameters (reduced models) were selected in all cases.

4.5.4.1 Results for Four-Lanes with Divided Median (4D)

Model results for 4D segments are reported in Table 22. The results revealed an increase in KABCO, KABC, and PDO crashes as outside through lane widths is decreased. The increase in crashes was significant when tested at 95% confidence level with *p*-values of 0.010, 0.044 and 0.0153 for the outside through lane width. The effect of the inside lane width was insignificant, therefore the coefficient was removed. Also, the increase in median opening density resulted in the increase of KABCO, KABC, and PDO crashes. This was evident as the *p*-values of 0.0167, 0.0165, and 0.0315 for KABCO, KABC, and PDO crashes were observed. These results were consistent to the Mauga and Kaseko (2010) study which observed the increase in injury crashes with an increase in median opening density.

4.5.4.2 Results for Four-Lane Segments with TWLTL Median (5T)

Table 23 presents the model results for 5T segments. According to the results reported in Table 22, both KABCO and KABC crashes increased with reduced lane width for both lanes (inside and outside). The results were significant at 95% confidence level. For KABC crashes, *p*-values of 0.0184 and 0.0294 for inside and outside through lane, respectively, were observed while for KABCO crashes, *p*-values for inside and outside were 0.0493 and 0.0106, respectively.

Both KABCO and KABC crashes were significantly correlated to driveway density. The increase in driveway density resulted in the increase in KABCO and KABC crashes. *P*-values of 0.0334 and 0.0007 for KABCO and KABC crashes, respectively, were observed. This finding is consistent to the results reported by Mauga and Kaseko (2010) which observed the increase in injury crash rate as driveway densities were increased. However, with respect to PDO crashes, the inside lane width and driveway densities were found to be insignificant not only at 95%, but also at 90% confidence level.

4.5.4.3 Combined Summary of Results for 4D and 5T for Key Variables

As it is shown in HSM (2010), the influence of ADT was found to be significant for all three response variables (KABCO, KABC and PDO crashes) at 95% confidence level. The model yielded p-values of 0.0001, 0.0001 and 0.0001 for KABCO, KABC and PDO crashes respectively for 4D and 0.0001, 0.0001, 0.0111, for 5T. In all cases for the 5T, the level of significant for segment length was not reported as it was used as an offset variable, i.e. with a constant coefficient of 1.000 for all three response variables.

Table 22 Results for Curb-and-gutter Four-Lane Roadways with Divided Median (4D)

KABCO Crashes				
Parameter	**Estimate**	**Standard Error**	***p*-values**	**Comment**
Intercept	-33.1729	4.8553	<.0001	*Significant
Ln of ADT	3.7903	0.4586	<.0001	*Significant
Ln of length	0.3505	0.126	0.0054	*Significant
Outside through lane width (ft)	-0.3591	0.1395	0.0101	*Significant
Median opening density	0.1713	0.0716	0.0167	*Significant
Deviance(Value/*df*):	1.12			
Over-Dispersion Parameter *k*:	1.51			
BIC:	1198.95			
AIC:	1177.82			
Pearson χ^2 (Value/*df*):	1.04			
KABC Crashes				
Intercept	-31.8083	5.321	<.0001	**Insignificant**
Ln of ADT	3.5618	0.5011	<.0001	*Significant
Ln of length	0.3944	0.1391	0.0046	*Significant
Outside through lane width (ft)	-0.3113	0.1546	0.044	*Significant
Median opening density	0.1921	0.0802	0.0165	*Significant
Deviance (Value/*df*):	1.05			
Over-Dispersion Parameter *k*:	1.71			
BIC:	1002.31			
AIC:	981.98			
Pearson χ^2 (Value/*df*):	1.01			
PDO Crashes				
Intercept	-38.6478	5.6048	<.0001	**Insignificant**
Ln of ADT	4.2327	0.5342	<.0001	*Significant
Ln of length	0.3038	0.1444	0.0354	*Significant
Outside through lane width (ft)	-0.3743	0.1544	0.0153	*Significant
Median opening density	0.1584	0.0736	0.0315	*Significant
Deviance (Value/*df*):	1.01			
Over-Dispersion Parameter *k*:	1.51			
BIC:	869.59			
AIC:	849.26			
Pearson χ^2 (Value/*df*):	1.03			

**Significant at 5% level*
***Significant at 10% level*

Table 23 Results for Curb-and-gutter Four-Lane Roadways with TWLTL (5T)

KABCO Crashes				
Parameter	**Estimate**	**Standard Error**	***p*-values**	**Comment**
Intercept	7.9121	6.8456	0.2478	**Insignificant**
Ln ADT	1.0190	0.2412	<.0001	*Significant
Driveway density	0.0504	0.0237	0.0334	*Significant
Outside through lane width (ft)	-0.5887	0.2305	0.0106	*Significant
Inside Lane width (ft)	-0.6318	0.3214	0.0493	*Significant
Deviance(Value/*df*):	1.11			
Over-Dispersion Parameter *k*:	1.07			
BIC:	999.53			
AIC:	979.56			
Pearson χ^2 (Value/*df*):	1.38			
KABC Crashes				
Intercept	5.6102	6.7447	0.4055	**Insignificant**
Ln ADT	1.1963	0.2523	<.0001	*Significant
Driveway density	0.0823	0.0243	0.0007	*Significant
Outside through lane width (ft)	-0.4978	0.2285	0.0294	*Significant
Inside Lane width (ft)	-0.7452	0.3162	0.0184	*Significant
Deviance (Value/*df*):	1.09			
Over-Dispersion Parameter *k*:	0.87			
BIC:	795.99			
AIC:	815.96			
Pearson χ^2 (Value/*df*):	1.40			
PDO Crashes				
Intercept	-1.2237	3.9480	0.7566	**Insignificant**
Ln ADT	0.9114	0.3587	0.0111	*Significant
Outside through lane width (ft)	-0.4092	0.1835	0.0258	*Significant
Deviance (Value/*df*):	0.90			
Over-Dispersion Parameter *k*:	2.14			
BIC:	676.39			
AIC:	659.75			
Pearson χ^2 (Value/*df*):	1.14			

4.5.5 Safety Performance Factors for PDO, KABC and KABCO Crashes

Using the regression model in Equation 15, baselines Safety Performance Functions (SPFs) for KABCO, KABC and PDO crashes were developed. The estimated values reported in Table 22 and 23 above were used as coefficients for variables. A total of six equations were developed as shown below. For 4D configuration, only the outside through lane width, inside lane width and median opening density were used as shown on Equations 16 to 18. For 5T configuration, KABC and KABCO crashes, ADT, driveway density, inside and outside through lane widths were used to form SPFs while for PDO crashes only ADT and outside through lane width were used. Equations 19 to 21 are the resulting SPFs derived from Equation 15 using model coefficients presented in Table 22 and 23.

4D Safety Performance Functions

SPF for KABCO Crashes:

$$ln(\mu_{KABCO}) = -33.17 + 3.79ln\ ADT\ \ +0.35\ln\ L\ \ + 0.17x_{Med\ open\ density} - 0.36x_{Out\ width} \qquad (16)$$

SPF for KABC Crashes:

$$ln(\mu_{KABC}) = -31.81 + 3.56ln\ ADT\ \ +0.39\ ln\ L\ \ + 0.19x_{Med\ open\ density} - 0.31x_{Out\ width} \qquad (17)$$

SPF for PDO Crashes:

$$ln(\mu_{PDO}) = -38.65 + 4.23ln\ ADT\ \ + 0.30\ ln\ L\ \ +0.16x_{Med\ open\ density} - 0.37x_{Out\ width} \qquad (18)$$

5T Safety Performance Functions

SPF for KABCO Crashes:

$$ln(\mu_{KABCO}) = 7.91 + 1.09ln\ ADT\ \ +0.05x_{Drwy\ density} - 0.59x_{Outer\ width} - 0.63x_{Inner\ width} \qquad (19)$$

SPF for KABC Crashes:

$$ln(\mu_{KABC}) = 5.61 + 1.19ln\ ADT\ \ +0.082x_{Drwy\ density} - 0.50x_{Out\ width} - 0.75x_{In\ width} \qquad (20)$$

SPF for PDO Crashes:

$$ln(\mu_{PDO}) = -1.96 + 0.91ln\ ADT\ \ -0.41x_{Outer\ width} \qquad (21)$$

4.6 Developing Crash Modification Factors

Crash Modification Factors (CMFs) quantify the change in expected average crash frequency (crash effect) caused by implementing a particular treatment. Treatment may be in a form of countermeasure, intervention, action, alternative, design modification, or change in operations. CMFs reflect the recognition that a change in geometry, traffic control device or signalization could result in either an increased or a decreased crash frequency. Normally, CMFs are used to estimate the expected number of crashes for a specific location, or estimate the effect of a change in conditions of a particular site on safety.

The value of CMF below 1 indicated treatment resulted to less crashes and CMF of 1 represents no effect on safety, while CMFs above 1 indicated that the treatment is expected to result in an increased number of crashes.

4.6.1 Method Used

The Highway Safety Manual provides a list of methods that can be used for developing CMFs. The most preferred method is the Empirical Bayes method using the before and after data. Due to the difficulty in obtaining the data on the exact date that a treatment was implemented, the before-and-after analysis was not feasible for this study. One of the methods mentioned by HSM i.e., the cross-sectional method was therefore adopted as it does not require the before and after data for analysis.

Instead, it employs the treatment and comparison sites for analysis. This method has been used by Lord and Bonneson (2007) to estimate Crash Modification Factors (CMFs) for rural frontage roads in Texas. The method estimates CMFs by using the coefficients of regression models developed as SPFs, for this case, SPFs developed in the previous section of this chapter. CMFs for each specific variable follow exponential relationship as shown in Equation 22.

$$CMF_i = e^{\beta_i[x_i - y_i]} \tag{22}$$

Where

x_i= range of values or a specific value investigated (e.g. lane width, etc.)
y_i = baseline conditions or average conditions for the variable
β_i= regression coefficient

4.6.2 Description of Base Conditions

Base conditions were developed using values from previous studies or from averaged values of individual variables. For example, the average values for driveway density was found to be 5 per 0.1 mile segment. For the case of segment length and speed base values, their mean values taken directly from Table 20 and 21 were used. However, when considering inside and outside through lane widths, the values for both were derived directly from previous studies. Table 24 shows a list of base conditions for each design element.

Table 24 Base Conditions for Different Design Elements

Design Elements	Base Conditions
Inside lane width	12 ft (measured between the centers)
Outside through lane width	12 ft (measured from the lip of the gutter)
Presence/type of median	TWLTL
Speed category	40 mph
Segment length	0.1mile
Median opening density	1 opening/0.1 mile
Drive-way density	5 driveway/0.1mile
Presence/type of on-street parking	Not present
Roadside fixed object density	None
Average offset to roadside fixed objects from edge of traveled way	None
Presence of automated speed enforcement	None

4.6.3 Crash Modification Factors for Lane Widths

CMFs utilized base conditions defined in Table 24. Having defined base conditions the next step was to develop CMFs for four-lane roadways with median (4D) and four-lane roadways with TWLTL type of median (5T). The regression coefficients for SPFs developed in previous subsection were used. The baseline condition for both inside and outside through lane width was 12 ft. Since CMFs are multiplicative factors when they are used to predict crash frequencies, the CMFs were derived as

4D Crash Modification Functions

CMF for KABCO Crashes

$$CMF_{KABCO} = e^{-0.36[x_{outer}-12]} \tag{23}$$

CMF for KABC Crashes

$$CMF_{KABC} = e^{-0.31[x_{outer}-12]} \tag{24}$$

CMF for PDO Crashes:

$$CMF_{PDO} = e^{-0.37\ x_{outer}-12} \tag{25}$$

5T Crash Modification Functions

CMF for KABCO Crashes:

$$CMF_{KABCO} = e^{-0.59[x_{outer}-12]}.e^{-0.63[x_{inner}-12]} \tag{26}$$

CMF for KABC Crashes:

$$CMF_{KABC} = e^{-0.50[x_{outer}-12]}.e^{-0.75[x_{inner}-12]} \tag{27}$$

CMF for PDO Crashes:

$$CMF_{PDO} = e^{-0.41[x_{outer}-12]} \tag{28}$$

One of the challenges of this study was that there were no existing CMFs that were developed either for urban or rural roads that have addressed the issues of variation of inside and outside through lane widths. Therefore, there were no existing CMF equations to compare the results. It is worth noting that, from Section 4.5.5, the inside lane width for 5T configuration was found to be insignificant for PDO crashes. Therefore, CMF for the PDO crashes did not include coefficient of inside lane width.

4.6.4 Crash Modification Factor Curves and Interpretation

Figures 28 through 33 illustrate CMF curves for KABCO, KABC, and PDO. The six curves were developed by substituting varying lane widths – 11 to 12 ft for inside and 12.5 to 14 for outside through lane widths, in Equations 23 through 28. The base CMF was 1.00 corresponding to the inside or outside through lane width of 12 ft each.

When considering different combination of inside and outside through lane widths, the following observation were made for 5T configuration with KABCO crashes: the combination of 11 ft inside and 13 ft outside through lane width and the combination of 11.5 ft inside and 12.5 ft outside through lane width resulted to CMF =1.00. This indicated to have neither increased nor reduced crashes. However, the combination of 11.5 ft and 13 ft resulted to CMF = 0.75 which indicated less crashes relative to 12 ft inside and 12 ft outside through lane width combination.

For KABC crashes, the combination of 11 ft inside and 13 ft outside or 11.5 ft inside and 12.5 ft outside both resulted to CMF greater than 1.00 which indicated an increase in crashes while the combination of 11.5 ft and 13 ft resulted to CMF lower than 1.00 which indicated a decrease in crashes. However, when considering PDO crashes, it was outside through lane width which had effect to CMF and as the width increased to more than 12 ft the CMF was less than one indicating crash reduction.

For 4D configuration PDO crashes, the increase of outside through lane width from 12 ft to 14.5 ft resulted in the decrease in CMF from 1 to 0.4 for KABCO and PDO. While for KABC the decrease in CMF is up to 0.44. This indicates a decrease in crashes as the outside through lane width is increased.

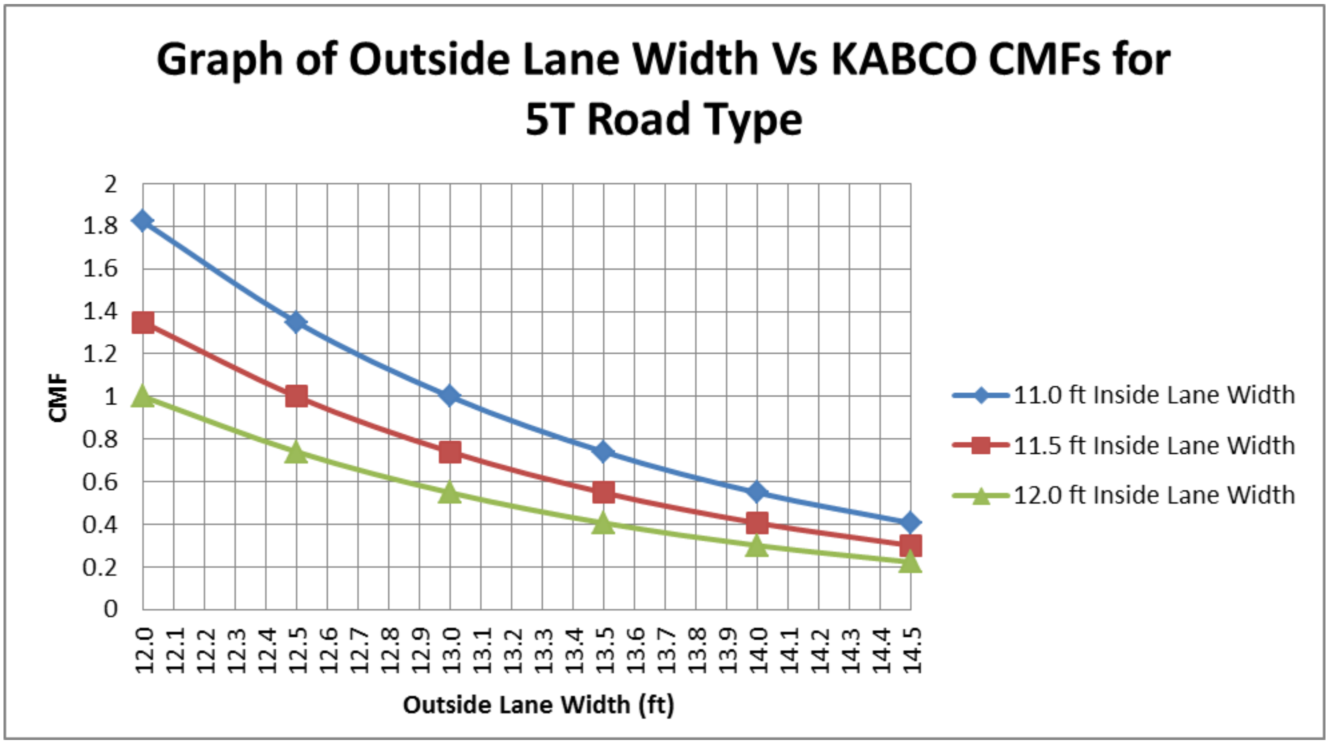

Figure 28 Graph of CMF for KABCO crashes under different lane widths for inside and outside

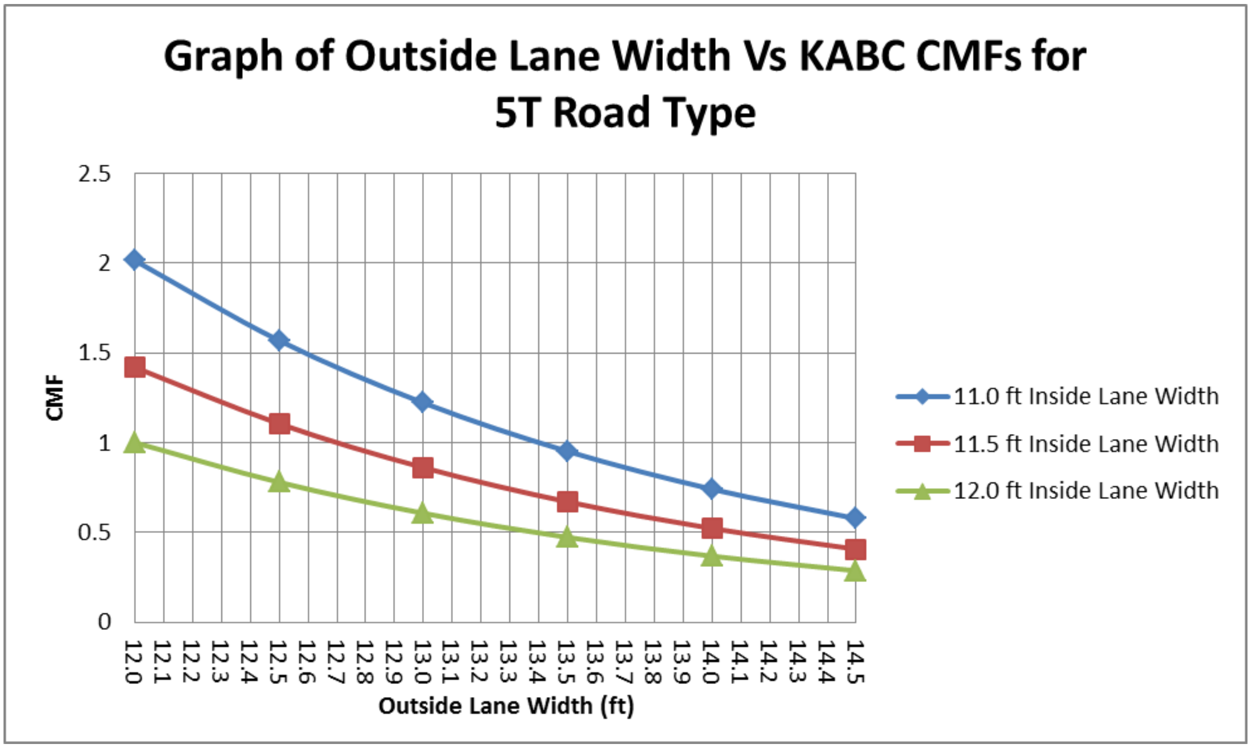

Figure 29 Graph of CMF for KABC crashes under different lane widths for inside and outside lanes

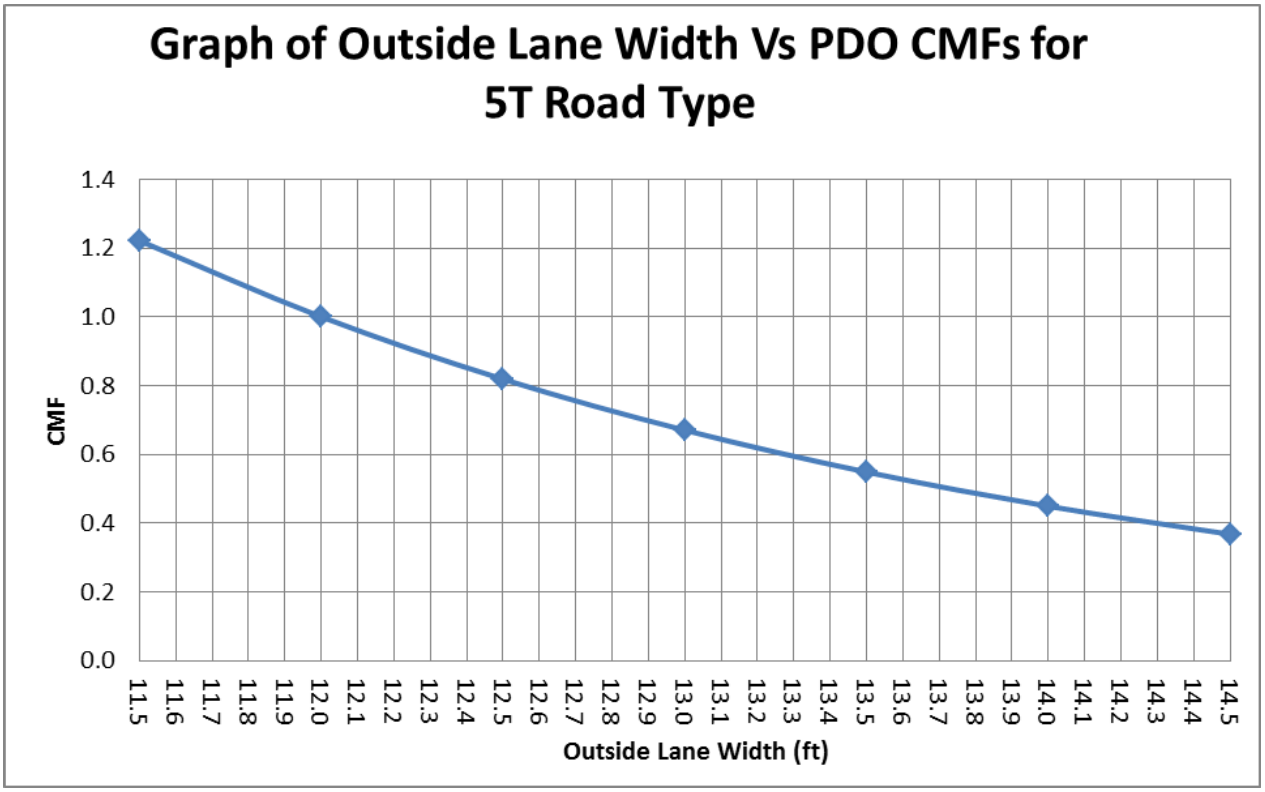

Figure 30 Graph of CMFs for PDO crashes under different lane widths for outside through lanes

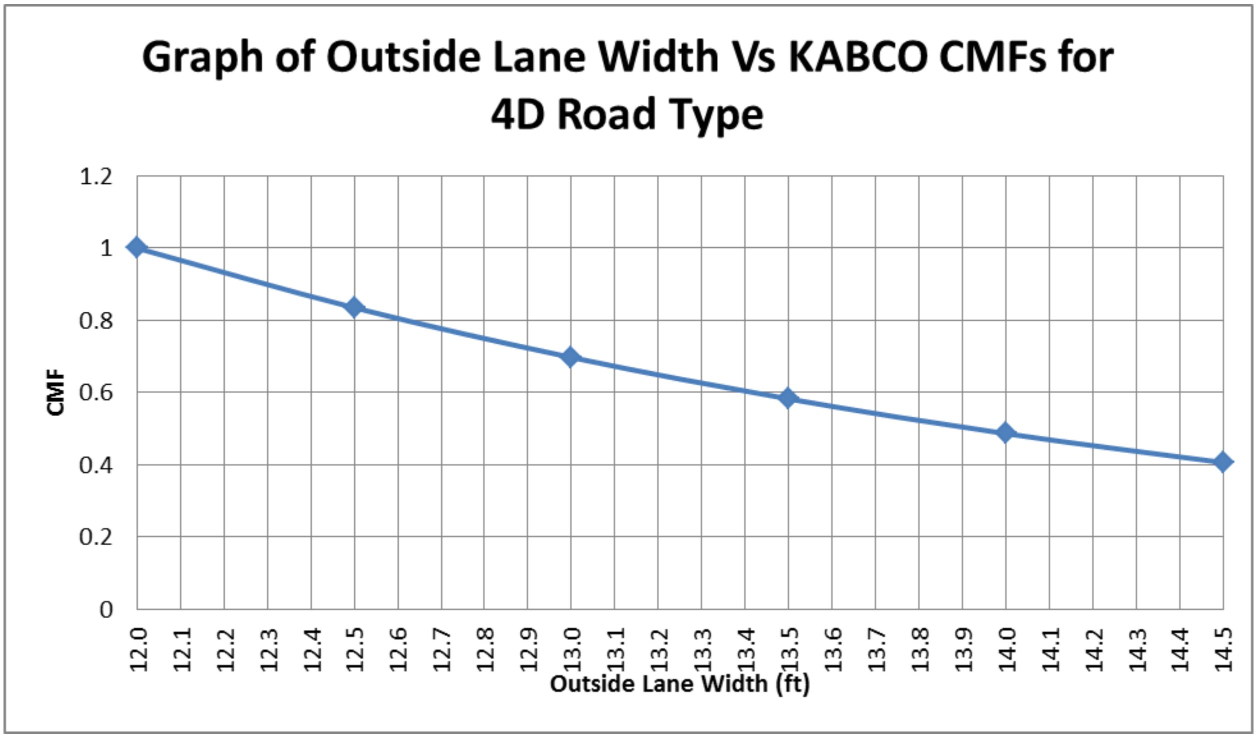

Figure 31 Graph of CMF for KABCO crashes under different lane widths for outside through lanes

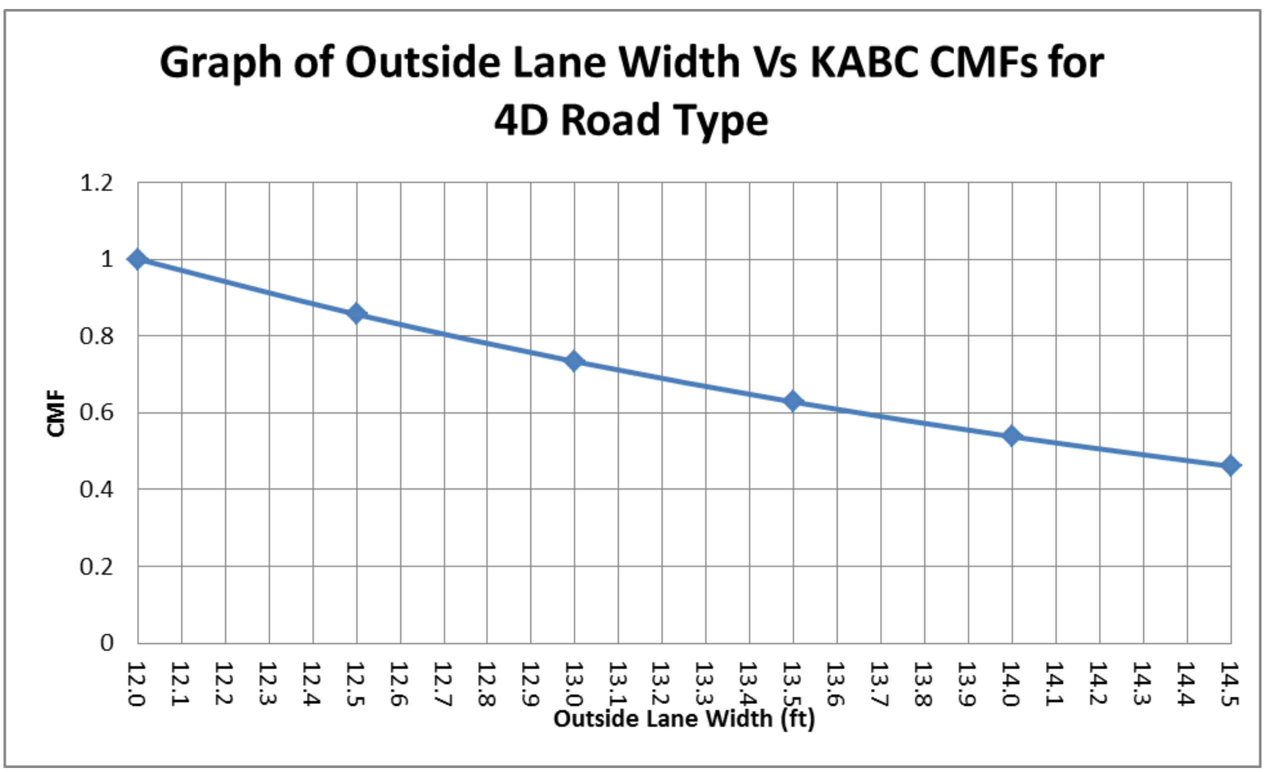

Figure 32 Graph of CMF for KABC crashes under different lane widths for outside through lanes

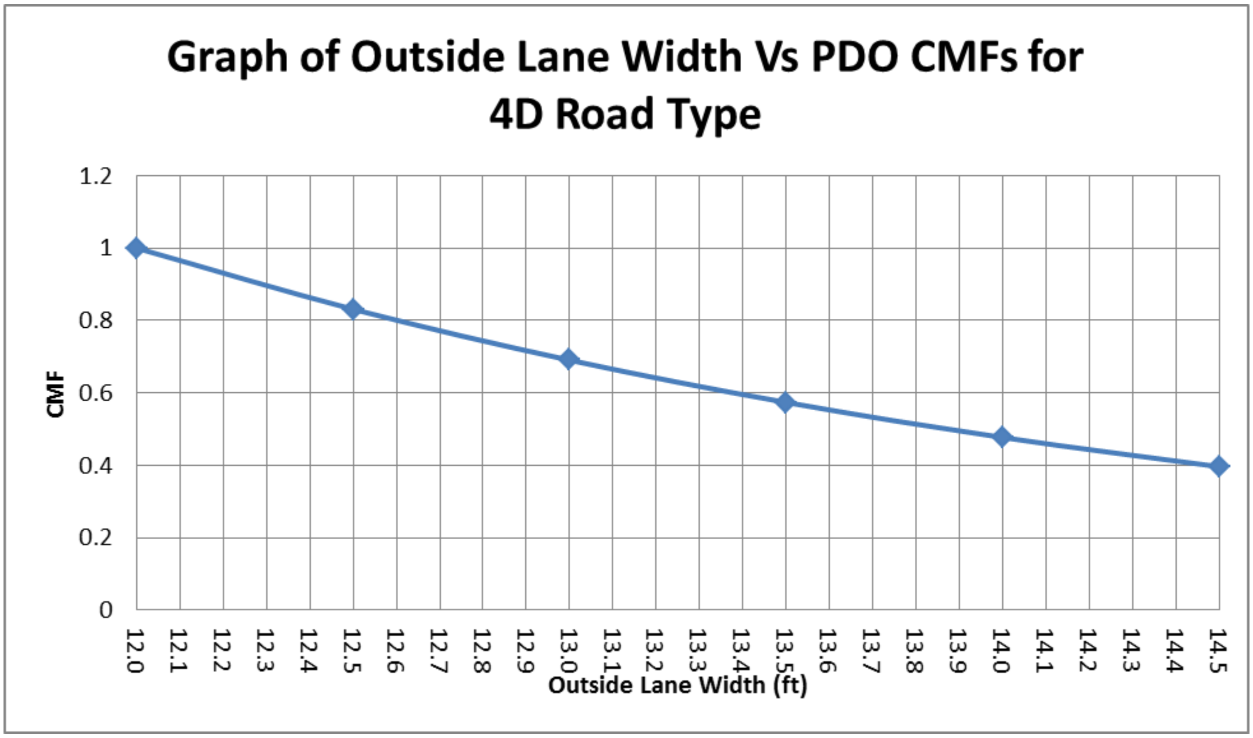

Figure 33 Graphs of CMFs for PDO crashes under different lane widths for outside through lanes

The comparison was made between the CMFs developed for 4D (four-lane with divided median) and 5T (four-lane with TWLTL median) when inside lane width is fixed to 11 ft while outside through lane width varied from 12.5 ft to 14.5 ft. The CMFs developed were for all severity levels of crashes (KABCO), i.e. {Fatal (K), incapacitating-injury (A) non-incapacitating injury (B) possible injuries (C) property damage only (O) crashes} KABC i.e. {Fatal (K), incapacitating-injury (A) non-incapacitating injury (B) possible injuries (C) crashes} and Property damage only crashes abbreviated as PDO. Results are summarized in Table 25.

A CMF of 1.00 indicates no influence in causing crashes while CMFs of smaller and greater than 1.00 indicate that a change of a variable from a base value causes a decrease and increase in crashes, respectively. According to the results, crashes decrease as the outside through lane width is increased from 12 ft. This decrease is seen on all types of crashes analyzed in this study, i.e., KABCO, KABC, and PDO crashes. According to the results depicted in Table 25, for 4D segments, the effect of inside lane width is insignificant, indicating that the decrease of lane width from 12 ft to 11 ft does not cause an increase in crash frequency.

Table 25 Comparison of CMF for 4D and 5T when Inside Lane Width is Fixed to 11 ft While Outside through lane Width Varied

	Base Line Condition	[4D CMF] (5T CMF) Ratio (5T CMF)/(4D CMF)					
Outside Lane Width Range (ft)	11.8-12.2	11.8-12.2	12.3-12.7	12.8-13.2	13.3-13.7	13.8-14.2	14.3-14.7
Outside Lane Width (ft)	12	12	12.5	13	13.5	14	14.5
Inside Lane Width Range (ft)	11.8-12.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2	10.8-11.2
Inside Lane Width (ft)	12	11	11	11	11	11	11
CMF for KABCO Crashes	[1.00] (1.00) 1.00	[1.00] (1.88) 1.88	[0.84] (1.40) 1.67	[0.70] (1.04) 1.49	[0.58] (0.77) 1.32	[0.49] (0.58) 1.18	[0.41] (0.43) 1.05
CMF for KABC Crashes	[1.00] (1.00) 1.00	[1.00] (2.12) 2.12	[0.86] (1.65) 1.92	[0.73] (1.28) 1.75	[0.63] (1.00) 1.59	[0.54] (0.78) 1.44	[0.64] (0.61) 0.95
CMF for PDO Crashes	[1.00] (1.00) 1.00	[1.00] (1.00) 1.00	[0.83] (0.81) 0.98	[0.69] (0.66) 0.96	[0.57] (0.54) 0.95	[0.48] (0.44) 0.92	[0.40] (0.36) 0.9

For 5T sections, the results show an increase in crashes as the inside lane width is reduced to 11 ft while the outside through lane width is increased to 12.5 ft. This trend was observed for both KABCO and KABC crashes, but not for PDO crashes. CMFs for PDO crashes were found to be independent of the inside lane width, but dependent of outside through lane width. Relative to outside through lane width of 12 ft, the CMFs for PDO crashes were found to decrease as the outside through lane width increased.

As stated above, for 4D segments, narrowing the inside lane from 12 ft to 11 ft did not result in an increase in crash frequency for any of the three types of crashes. Also, for 5T segments, the decrease in inside lane width was not significant for PDO crashes. It was only significant for KABCO and KABC crashes, hence higher CMF values for KABCO and KABC crashes for 5T. As far as 5T segments are concerned, higher CMF values for KABCO and KABC crashes might have been attributed to the type of median and might have less to do with the inside lane width. Having higher values of CMFs for KABCO and KABC crashes on roads with a TWLTL is consistent with studies by Mauga and Kaseko (2010) and 15 studies reviewed by Gluck *et al*. (1999). These studies reported crash reduction that range from 3% and 57% for KABCO crashes on roads with raised median in comparison to segments with TWLTL. Mauga and Kaseko (2010) also found a decrease of 21% on KABC crashes for roads with raised median in comparison to those with TWLTL.

Table 25 also shows the ratio between the CMFs developed for 4D and 5T segments with a fixed inside lane of 11 ft while outside through lane width varied from 12.5 ft to 14.5 ft. The results revealed that with respect to KABCO crashes, the CMF for 5T segments, when the inside lane width is 11 ft and the outside through lane width is 12 ft is 1.88 times that of 4D segments. The ratio decreases as the outside through lane width increases from 12.5 ft to 14.5ft, where the 5T CMF is 1.05 times that of 4D segments. A similar trend was observed for KABC crashes as the ratio decreased from 2.12 to 0.95 as the outside through lane width increased from 12 ft to 14.5 ft while keeping the inside lane width constant at 11 ft. As can be seen in Table 25, for PDO crashes, the ratio of CMFs for 4D segments to CMFs for 5T segments is smaller than 1.0, indicating that for PDO crashes, a higher crash reduction is expected for 5T segments than for 4D segment when the outside through lane width is widened while keeping the inside lane fixed at 11 ft.

In order to answer the research question, i.e., whether the provision of outside lane widths less than 14 ft offers any safety benefits, one needs to compare typical with asymmetrical lane configurations with the same total pavement width. When comparing a typical 12 ft inside and a 12 ft outside through lane width segment (a total of 24 ft) with an asymmetric segment of an 11 ft inside lane and a 13 ft outside through lane, the results in Table 25 show that a 4D asymmetric lane configuration would result in fewer crashes (See highlighted cells - CMFs of 0.70, 0.73, and 0.69 for KABCO, KABC, and PDO crashes, respectively). For 4D configurations, given a total of 24 ft pavement width for both lanes, the results presented in Table 25 indicate that restriping a roadway 12 ft to an 11 ft inside and a 13 ft outside through lane would result in a decrease in crashes. For 5T sections, the results are mixed, showing a slight increase for KABCO and KABC crashes (CMFs of 1.04 and 1.28, respectively) and a reduction of PDO crashes (CMF of 0.66), when a typical roadway is retrofitted to an 11 ft inside and a 13 ft outside through lane, respectively. The results also show that as the width of outside lane increases, for both 4D and 5T configurations, crashes decrease.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

This study developed lane width crash modification factors (CMFs) for roads with asymmetrical lane width configuration narrower than or equal to 14 ft, and inside lanes ranging from 11 to 12 ft. CMFs were developed for curb-and-gutter four-lane segments with a divided median and four-lane two-way left-turn lane (TWLTL). Data used in the evaluation included 25 centerline miles of curb-and-gutter four-lane (TWLTL) roads and 39 centerline miles of four-lane with a divided median roads.

Negative binomial regression models were used to develop Safety performance functions (SPFs) which established the effects of independent variables on crashes. Variables considered in developing the base models for SPFs included driveway density, median opening density, inside lane width, outside through lane width, median width, segment length, and average daily traffic (ADT). Six years (2004–2009) of segment crashes were examined. A cross-sectional method was used to develop CMFs for all severity levels of crashes, fatality and injury crashes, and property damage crashes only.

The results of this study are presented in graphs and tables shown in Chapter 4. According to the results depicted in Figures 28 to 33 and Table 25, for 4D segments, the effect of inside lane width is insignificant, indicating that the decrease of lane width from 12 ft to 11 ft does not cause an increase in crash occurrences. According to the results, crashes decrease as the outside through lane width is increased from 12 ft. This decrease is seen on all types of crash severities, i.e. KABCO, KABC and PDO.

For 5T sections, the results show an increase in crashes as inside lane width is reduced to 11 ft while the outside through lane width was increased to 12.5 ft. This trend was observed for both KABCO and KABC, but not for PDO. However, the combination of 11.5 ft or more for inside lane and 13 ft for outside through lane width showed the decrease in crashes for KABCO and KABC. CMFs for PDO crashes were found to be independent of inside lane width, but dependent of outside through lane width. Relative to outside through lane width of 12 ft, the CMFs for PDO crashes were found to decrease as lane width was increased from 12 ft.

As stated above, reducing the inside lane from 12 ft to 11 ft did not result in an increase of all types of crashes for 4D segments. Also, for 5T, the decrease in inside lane width was not significant when considering PDO crashes. It was only significant when considering KABCO and KABC crashes, hence higher values of CMFs for KABCO and KABC crashes for 5T. For 5T segments, higher CMF values for KABCO and KABC might have been attributed to the type of median and have less to do with the inside lane width as shown in Table 25. As illustrated in Chapter 4, TWLTL medians are known to have higher crash occurrences than raised medians.

5.2 Recommendations for Further Research

This study is not without limitations. The most preferred methods for developing CMFs are controlled experiments and observational before-and-after studies. This study used a cross-sectional method. A before-and-after method would have given more robust results but was not practical or feasible as exact dates when standard 12 ft lanes were retrofitted to create asymmetric lanes could not be obtained.

Lane width CMFs for curb-and-gutter roadways do not exist. Therefore, there were no existing CMF equations to compare the results with. The robustness of CMFs developed by statistical modeling is improved by using homogeneous sites, i.e., sites with similar properties, whereas the only variables are AADT, segment length, and the treatment variable, for this case, lane width. This was not practical as it was not possible to get sufficient segments with similar properties such as the posted speed limit, median opening density, and driveway density. Also, due to limited data, area type was not considered as a variable. A much wider study is recommended, which will develop lane width separate CMFs for residential, industrial, and central business district areas.

In addition, the available data could not allow for estimating the effect on bicyclists crashes. This area is under-represented in previous work. Therefore, additional attention should be paid to determining the safety implications from a lane width perspective. Last but not least, further research is needed to calibrate the developed CMFs to make them useful elsewhere other than Florida.

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APPENDIX A
A.1. A Blank Questionnaire

Questionnaire to solicit information on wide outside lanes in your district/area

Survey guide for bicycle and pedestrian coordinators

Contact Person:___________________________________
Title:____
City: ____
Address:____
Telephone: __________________Fax:________________
Email address:_____________________________________

The Florida Department of Transportation is sponsoring a research project to evaluate the operational and safety impacts of restriping inside lanes of urban multilane curbed roadways to 11 ft or less to create wider outside lanes for bicyclists. An example would be restriping an existing 4- lane roadway with 12' wide travel lanes and no bicycle facilities to create 13' wide outside through lanes and 11' wide inside lanes. The main objective of this research is to evaluate whether any safety and/or operational benefits are realized in using asymmetrical lane width configurations on multilane roadways to provide outside lane widths between 12 and 14 ft wide. More information about the project is available from the project manager and the principal investigator who can be reached using the following email addresses and phone numbers.

FDOT Project Manager: Mary Anne Koos; Contact Info: MaryAnne.Koos@dot.state.fl.us; (850) 414-4321
Principal Investigator: Thobias Sando; Contact Info: t.sando@unf.edu; (904) 620-1142

This questionnaire is designed to guide a person who is familiar with roadway geometry in their community to provide his/her best knowledge on the location of roadways with varying lane widths which could be considered for further study.

Use the attached spreadsheet to fill in answers for questions 1 to 3.

1. List bicycle corridors in your area that are multilane (4-lanes or higher – both directions) with outside curbed lanes wider than 12' and narrower than 14'.

2. The research team is interested in selecting sites for conducting an operation observational study, which involves collecting bicycle count data, video taping the interaction between bicyclists and motorists, and possibly conducting a survey to bicyclists. Indicate in the attached spreadsheet the corridors listed in question 1 which would be the best candidates for a field study. Also indicate the best time of day and times of year for capturing high bicycle volume.

3. Out of the streets listed in question 1, mark the ones that you know to the best of your knowledge that were retrofitted to outside lanes wider than 12’ and narrower than 14’ in the last 10 years.

4. Do you know any source that has documented the location and characteristics of bicycle facilities in your area or elsewhere in Florida? Yes___ No___

5. If the answer to question 4 is yes, list the sources that you are familiar with (include documents and/or web links).
   1____
   2____
   3____

6. Does the agency you represent have bicycle traffic counts and/or bicycle crash data? Yes___ No___

7. Any Comments/Remarks

____
____
____
____

Thank you for your participation in this important research aimed at enhancing safety and improving bicycle operations in the state of Florida. Please send the completed questionnaire by email, fax, or snail mail using the following contact information.

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Phone: 904-620-1142
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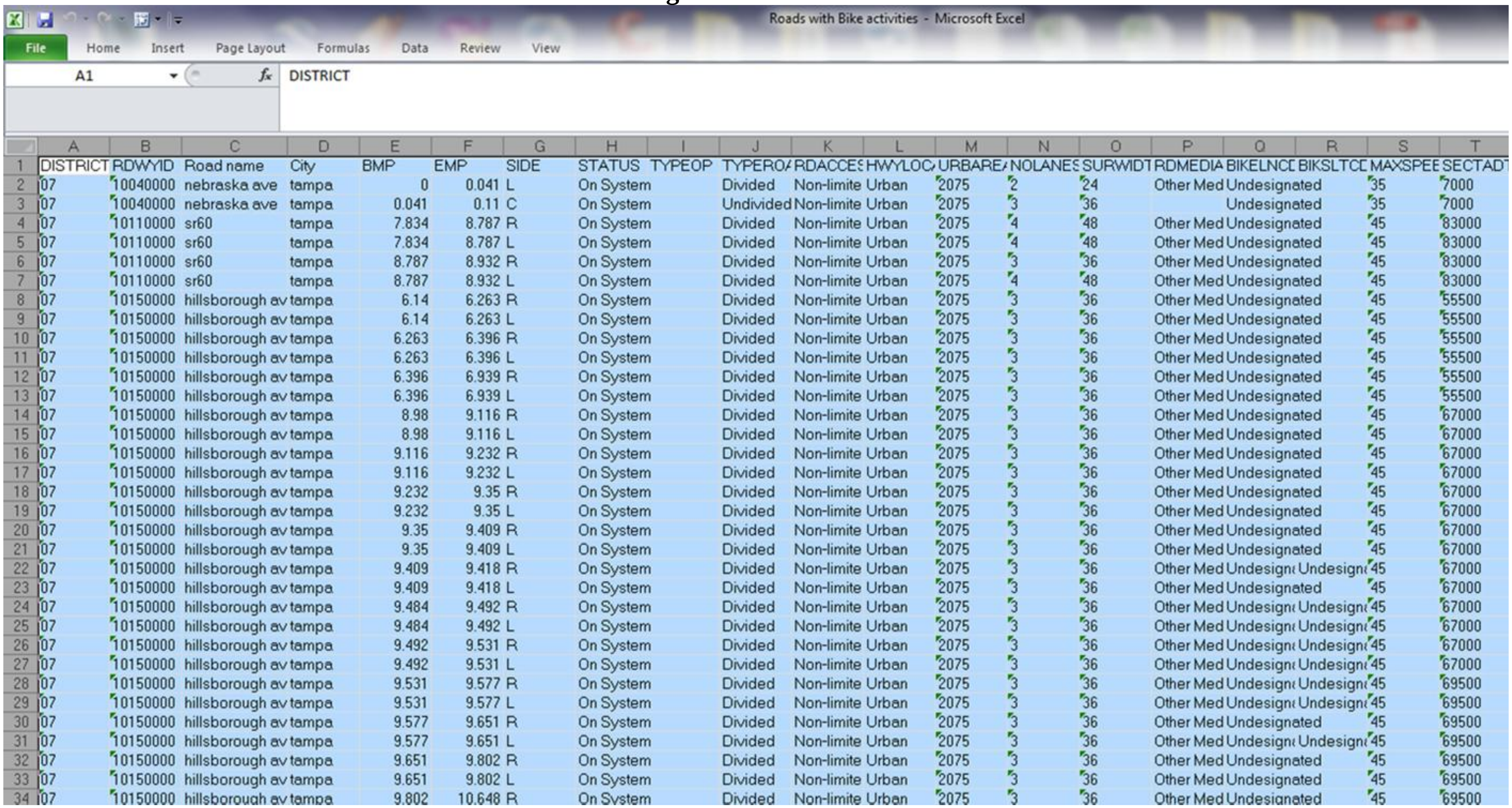
A.2. Image of RCI excel file



	DISTRICT	RDWYID	Road name	City	BMP	EMP	SIDE	STATUS	TYPEOP	TYPERO/	RDACCES	HWYLOC/	URBARE/	NOLANES	SURWIDT	RDMEDIA	BIKELNCD	BIKSLTCD	MAXSPEE	SECTADT
2	07	10040000	nebraska ave	tampa	0	0.041	L	On System		Divided	Non-limite	Urban	2075	2	24	Other Med	Undesignated		35	7000
3	07	10040000	nebraska ave	tampa	0.041	0.11	C	On System		Undivided	Non-limite	Urban	2075	3	36		Undesignated		35	7000
4	07	10110000	sr60	tampa	7.834	8.787	R	On System		Divided	Non-limite	Urban	2075	4	48	Other Med	Undesignated		45	83000
5	07	10110000	sr60	tampa	7.834	8.787	L	On System		Divided	Non-limite	Urban	2075	4	48	Other Med	Undesignated		45	83000
6	07	10110000	sr60	tampa	8.787	8.932	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	83000
7	07	10110000	sr60	tampa	8.787	8.932	L	On System		Divided	Non-limite	Urban	2075	4	48	Other Med	Undesignated		45	83000
8	07	10150000	hillsborough av	tampa	6.14	6.263	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
9	07	10150000	hillsborough av	tampa	6.14	6.263	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
10	07	10150000	hillsborough av	tampa	6.263	6.396	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
11	07	10150000	hillsborough av	tampa	6.263	6.396	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
12	07	10150000	hillsborough av	tampa	6.396	6.939	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
13	07	10150000	hillsborough av	tampa	6.396	6.939	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	55500
14	07	10150000	hillsborough av	tampa	8.98	9.116	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
15	07	10150000	hillsborough av	tampa	8.98	9.116	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
16	07	10150000	hillsborough av	tampa	9.116	9.232	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
17	07	10150000	hillsborough av	tampa	9.116	9.232	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
18	07	10150000	hillsborough av	tampa	9.232	9.35	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
19	07	10150000	hillsborough av	tampa	9.232	9.35	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
20	07	10150000	hillsborough av	tampa	9.35	9.409	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
21	07	10150000	hillsborough av	tampa	9.35	9.409	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
22	07	10150000	hillsborough av	tampa	9.409	9.418	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	67000
23	07	10150000	hillsborough av	tampa	9.409	9.418	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	67000
24	07	10150000	hillsborough av	tampa	9.484	9.492	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	67000
25	07	10150000	hillsborough av	tampa	9.484	9.492	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	67000
26	07	10150000	hillsborough av	tampa	9.492	9.531	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	67000
27	07	10150000	hillsborough av	tampa	9.492	9.531	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	67000
28	07	10150000	hillsborough av	tampa	9.531	9.577	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	69500
29	07	10150000	hillsborough av	tampa	9.531	9.577	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	69500
30	07	10150000	hillsborough av	tampa	9.577	9.651	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	69500
31	07	10150000	hillsborough av	tampa	9.577	9.651	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesign	Undesign	45	69500
32	07	10150000	hillsborough av	tampa	9.651	9.802	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	69500
33	07	10150000	hillsborough av	tampa	9.651	9.802	L	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	69500
34	07	10150000	hillsborough av	tampa	9.802	10.648	R	On System		Divided	Non-limite	Urban	2075	3	36	Other Med	Undesignated		45	69500

Figure 34 Image of RCI excel file

A.3. Image of as built plan drawing

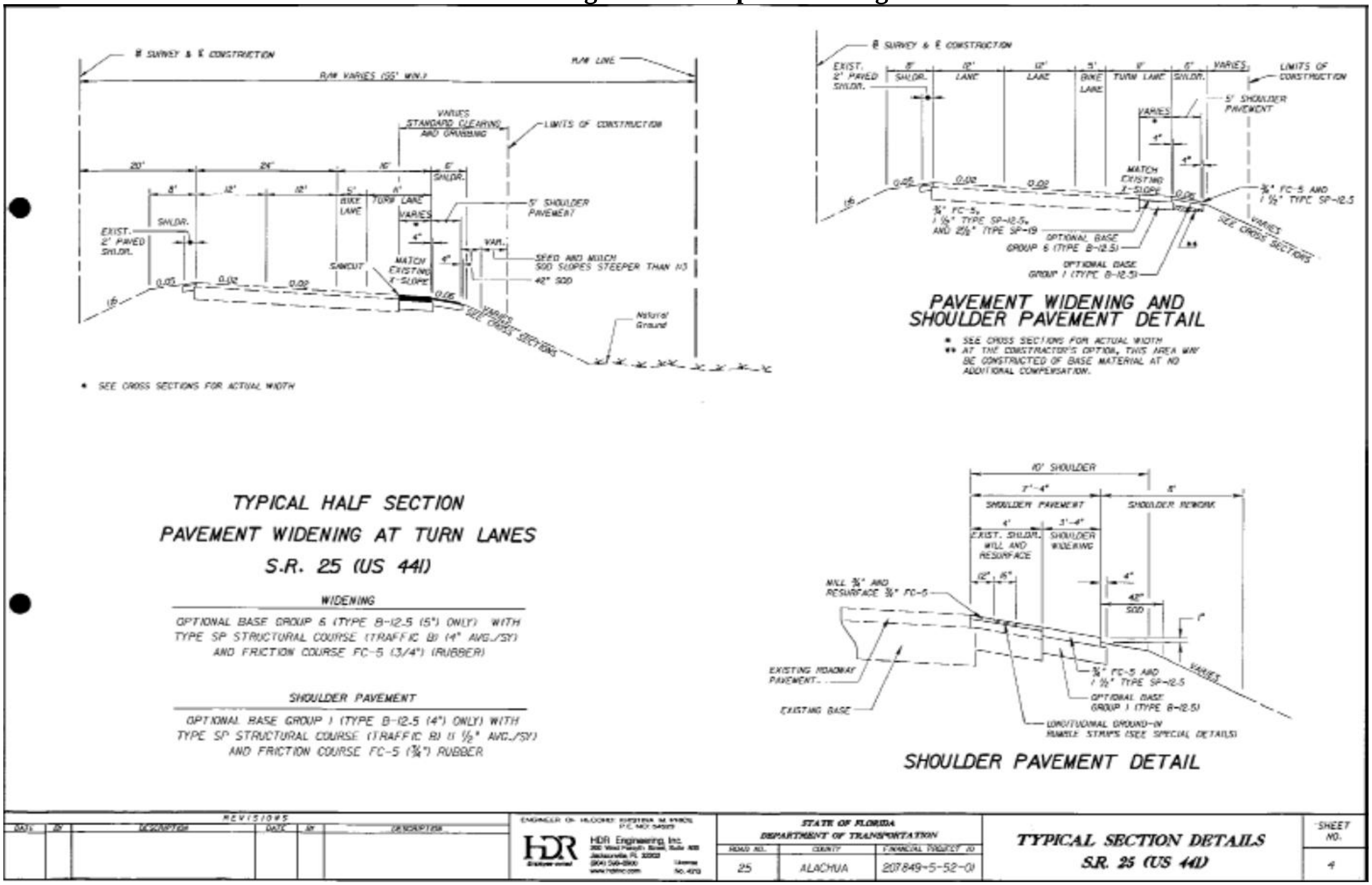


Figure 35 Image of as built plan drawing

A.4. Image of a straight line diagram

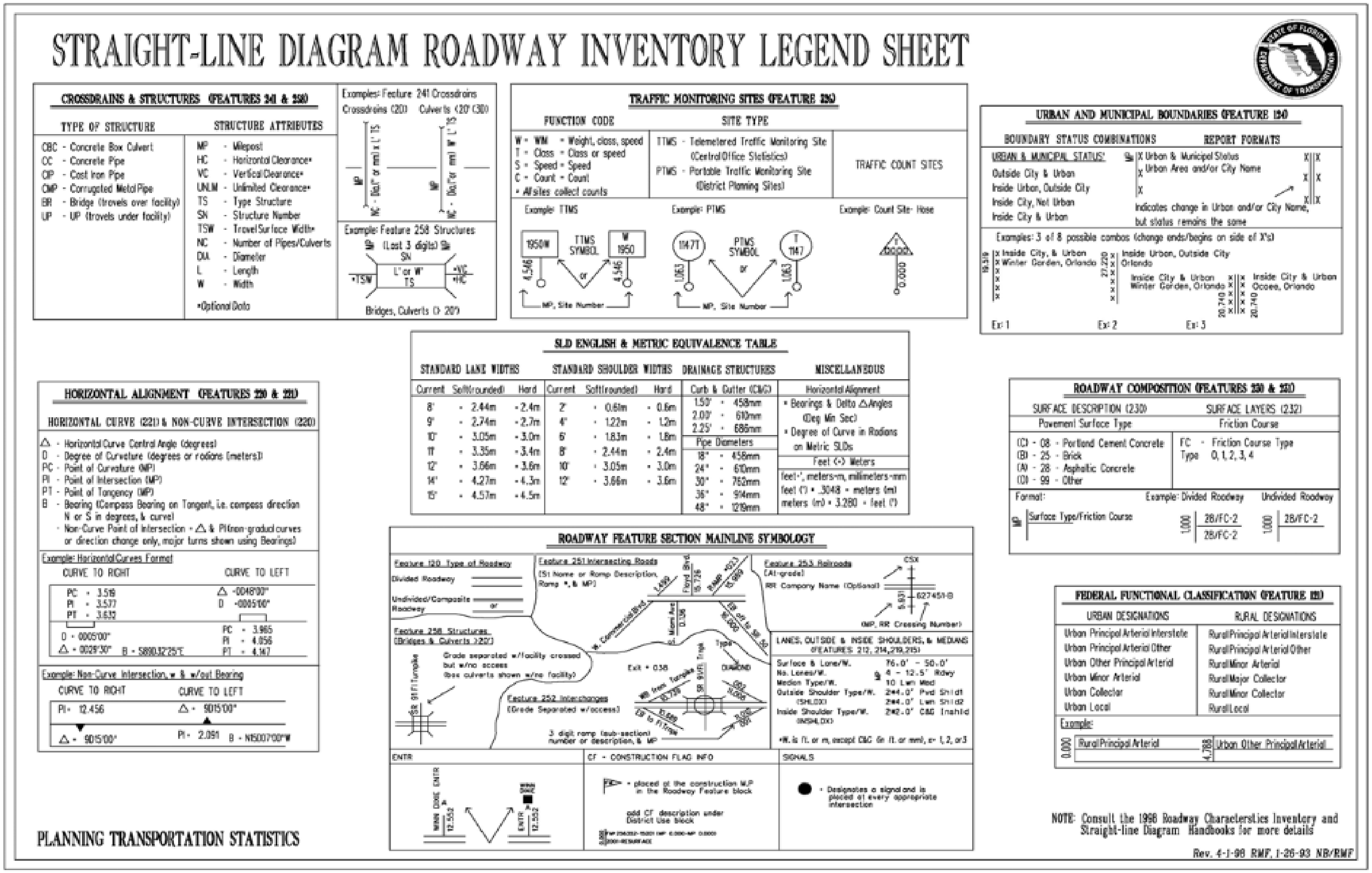


Figure 36 Image of a straight line diagram