NDOT Research Report

Report No. 300-12-803

Evaluation of Geometric Design Needs of Freeway Systems Based on Traffic and Geometric Data

October 2013

Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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EVALUATION OF GEOMETRIC DESIGN NEEDS OF FREEWAY SYSTEMS BASED ON TRAFFIC AND GEOMETRIC DATA

Submitted to

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October 20, 2013

ABSTRACT

In Las Vegas, Nevada, the increased traffic competes for the limited spaces available in the freeway system and thus reduces safety performance. This study identified geometric design issues on freeway systems in Las Vegas, Nevada, based on available safety data for freeway EN-EX and EX-EN segment types. For every segment, crash rate and severity models were developed. It was found that for EN-EX segment type, number of through lanes, curve radius, shoulder and median widths had a significant impact on average crash rate. The same geometric elements with an additional of AADT also indicated significant impact on severity crashes. Segments with large radius reduced average crash rate while it did not have an impact on severity crashes. Wide shoulders and medians reduced average crash rate and high severity crashes. Long segments reduced average crash rate while it did not indicate an impact on crash severity. The number of through lanes increased both average crash rate and high severity crashes. For EX-EN segments, curve with large radius, wide shoulders and medians reduced both average crash rate and high severity crashes. The number of through lanes increased average crash rate on I-15 while it reduced average crash rate on I-215. It did not have an impact on average crash rate on US 95. In addition, the number of through lanes increased the number of high severity crashes on I-15 and I-215 while it reduced high severity crashes on US95. High traffic volume increased average crash rate on I-215 while it did not indicate an impact on I-15 and US 95.

As far as countermeasures to improve safety, it was identified that on an EN-EX segment, congestions usually occur in the following two situations. First, weaving would happen between traffic streams on to freeway and that off from freeway. Either of these two traffic stream become heavy, the freeway would become congested, which need separating them spatially. When the traffic from the on-ramp is heavy, ramp metering can be installed, which is a way to mitigate congestion and reduce crash on freeway. Second, if the traffic on the off-ramp could not be clearly quickly, the queue would back up to freeway and then make the freeway congested. In this case, signals at the end of the off-ramp need to be adjusted to make the off-ramp traffic cleared on a timely manner. If this segment is long, warning signs would be recommended to warn motorists of the congestion downstream.

An EX-EN segment is usually at the middle of an interchange, one side for traffic getting off freeway and the other side getting on freeway. The congestions usually occur in the follows two situations. First, the traffic on to freeway become heavy, making the merging on freeway congested, and this congestion would quickly spill back to this segment. In this case, it is suggested to install ramp metering. When the traffic is extremely heavy, separating the traffic on to the freeway spatially from that goes through the downstream segment is necessary. If this segment is long, warning signs are suggested to install on this segment, alerting the motorists of the congestion downstream. Second, if the traffic getting off the freeway become heavy, congestion on the off-ramp would back up to the freeway, which would create traffic turbulences for traffic even after passing the point of off ramp.

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CHAPTER 1 INTRODUCTION

1.1. Motivation background

The Nevada traffic crash reports indicated that for year 2006 to 2010, a total of 176,858 crashes occurred. In 2010, the report indicated that 30,187 crashes occurred. Detailing these crashes by severity level, the report indicated that, 115 fatal crashes, 12,147 injury crashes and 17,925 property damage crashes were recorded with respective percentages as 0.38% fatal, 40.24% injury, and 59.38% property damage.

With respect to freeways, crash data obtained from NDOT indicated that a total of 1,661 crashes occurred on the freeway systems during the year 2010. Among these 12 (0.72%) crashes were fatal, 735 (44.25%) injury crashes and 914 (55.03%) property damage crashes. These data indicate that more severe crashes happened on freeways than on arterials, which need further investigation to improve safety performance. Different alternatives can be implemented to improve safety performance on freeways including increasing capacity at bottleneck locations, altering the geometrics to eliminate safety hazards, enhancing various attributes of the freeway environment (e.g., signing, pavement markings, illumination) to increase safety and driver convenience (FHWA 2011). Among these alternatives, those on geometric design are fundamental.

This research is intended to evaluate contributing factors to crash occurrence and recommend corresponding countermeasures in Las Vegas of Nevada. Four types of segments bounded by ramps can be found in Las Vegas of Nevada: EN-EX, EX-EN, EN-EN, and EX-EX where EN means an on-ramp and EX stands for off-ramp. Among them, the number of EN-EN and EX-EX segment types is very small and was not considered in the analysis in this study. This section covers a brief explanation of an overview of safety performance for EN-EX and EX-EN segment types in terms of their geometric elements and operation factors.

EN-EX segments

EN-EX segments have an on-ramp for entering vehicles and off-ramp for vehicles leaving the facility. The two ramps can either be joined by a continuous auxiliary lane (see Figure 1.1: a) or a limited auxiliary lane joining an on-ramp (see Figure 1.1: b) or an off-ramp (see Figure 1.1: c):

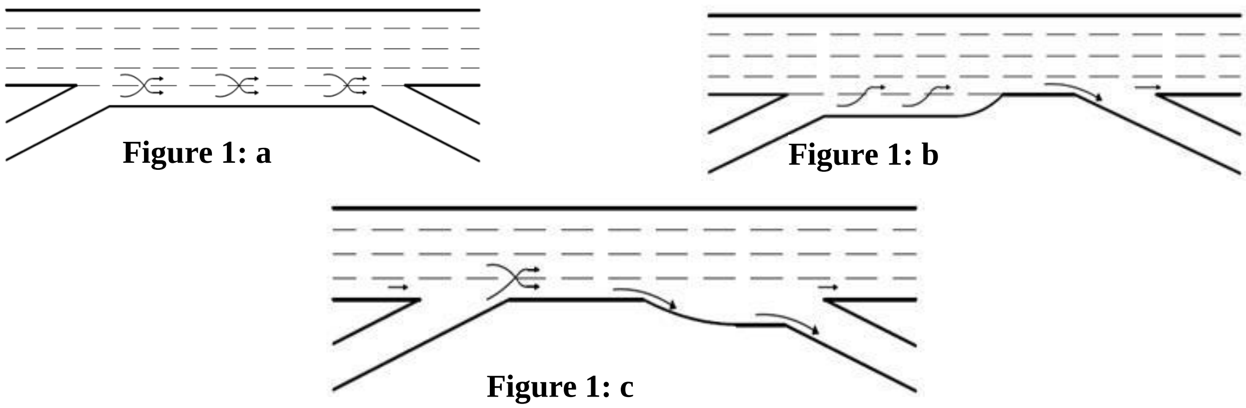


Figure1.1: EN-EX segment type configuration

These segments are called weaving segments (2010 Highway Capacity Manual). They are characterized by intense lane-changing maneuvers as drivers must access lanes appropriate for their desired exit point. Traffic flows in these segments is subjected to turbulence in excess of that normally present on other segment types.

Safety performance of these segments can be affected by its geometric elements such as the number of lanes on the main facility, segment length, curvature, shoulder and medians widths, and the total flows (AADT) experienced on the segments. Number of lanes may affect safety performance in two ways: More lanes on a segment induce lane-change activity and this can be thought of in two situations: In the first situation, the flow from the on-ramp merging with the main stream must cross the path of the flow leaving the main facility. The second situation occurs when vehicles that do not weave from one lane of the facility to the other make additional lane changes to avoid concentrated areas of turbulence within the segment. The turbulence created by lane changes increases the chance of collisions depending on the merging vehicle speed, acceptable gaps, and drivers' decision. With few number of lanes rear-end collisions are also likely to occur due to congestion.

Failure to maintain a safe following distance of the lead vehicle intending to exit the main facility, vehicle speed and short length of segments increase the chance of crash occurrence. Segments located in urban areas exhibit high density of entrance and exits tendencies and these increases more weaving leading to an increase in rear-end crashes on these segments (Golob et al. 2004). Sideswipe collisions may also be experienced when vehicles overtake each other on lanes that are not involved in weaving maneuvers. This happens when drivers intend to avoid lanes with high traffic flows. They are also more likely to occur on an on-ramps compared to off-ramps due to an increase in merging activity.

EX-EN segments

EX-EN segments have an off-ramp followed by an on-ramp and only through vehicular traffic is expected to use the segments (see Figure 1.2 below).

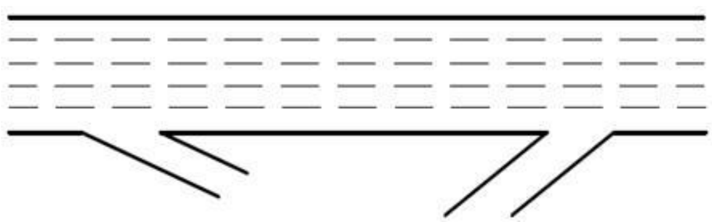


Figure1.2: EX-EN segment type configuration

Geometric elements likely to influence safety performance are the length of segments, the number of through lanes, curvature, narrow medians without barriers, and grade. Since the only traffic using the segments are through traffic, there will be less lane-changing activity because vehicles are not expected to exit at the next terminal. The segments are likely to experience rear-end, head-on, sideswipe, and angle crashes as a results of its geometric configuration. Rea-end crashes are likely to happen on these segments due to the congestion caused by the merging of on-ramp traffic to mainline at the segments downstream. They can be between two vehicles or chain-reaction rear-end crashes (Kim et al. 2007). Chain-reaction rear-end crashes are more likely with higher volumes which reduces the likelihood to reduce crashes. Truck percentage on freeways also contribute to an increase of occurrence of rear-end crashes. On the event that a leading vehicle is a truck, the following vehicles tend to switch lanes and overtake the truck due to slow speed of the truck. Rear-end crashes will increase if the maneuvers are erratic, there are more improper lane changes, and insufficient headway for a following truck after an overtake action. Few number of through lanes reflected by road congestion and driver distraction can also result in rear-end crashes. Head-on crashes had no predominant cause and can occur at all times (NCHRP Report 500-18). Factors which have been reported to contribute to head-on crash occurrence are narrow medians without barriers, high traffic volumes travelling at high speeds, and driver behavior. Narrow medians without barriers increase the likelihood of cross-over crashes. Driver behavior includes fatigue, inattention, and excessive speeding. Sideswipe crashes are mainly caused by unsafe lane-change actions, failure to stay in the lane, and disregard for pavement markings.

Different research activities have investigated the relationship of crashes on freeways to its geometric characteristics (Pilko et al., 2007; Ray et al., 2011; Fitzpatrick et al., 2010; Abdel-Aty, 2009; Sarhan et al., 2008; Golob et al., 2004; Chen et al., 2010; Qi et al., 2007). Table 1.1 shows every reference with freeway characteristics studied.

Results from these studies lead to different recommendations to improve safety performance of freeways. For instance, Fitzapatrick et al., (2010) proposed updates to current Texas Department of Transportation guidelines on recommended distances between ramps. The same task was also conducted by Ray et al., (2011). In their study relationship between ramp spacing and safety was discussed for three ramp combinations: EN–EX, EN–EN and EX–EN.

Instead of focusing on freeway segments between ramps or interchanges, weaving sections within the system were also investigated. Sarhan et al. (2008) found that for two acceleration lane with the same length, extended acceleration lanes increases collision frequency compared to limited acceleration lanes. Deceleration lanes were also found to have the same trend. The study also incorporated risk factors defining two types of weaving movements (Types A and B). In Type A, a vehicle makes one lane change to reach the desired terminal and in Type B one of the two weaving maneuvers could be accomplished without any lane change. The results indicated that Type B had the highest crash frequency.

Table 1.1: Previous studies with freeway characteristics

	References							
Freeway characteristics	**Golob et al., 2004**	**Pilko, et al., 2007**	**Qi, et al., 2007**	**Sarhan, et al., 2008**	**Chen, et al., 2009**	**Chen, et al., 2010**	**Fitzpatrick et al., 2010**	**Ray et al., 2011**
Length of segment			×	×			×	
Acceleration lane				×				
Deceleration lane				×				
Number of lanes		×	×	×				
Traffic volume	×		×	×	×			×
Type of weaving segments				×				
Speed limit					×		×	
Length of deceleration lane					×			
Number of lanes on exit ramps					×			
Left-side off-ramp						×		
Right-side off-ramp						×		
Horizontal curvature			×					
Interchange spacing		×						×
Shoulder width		×						
Lane change geometry	×							

Review of literature indicated that some of the studies consider just a few freeway characteristics. For instance, Qi (2007) considered horizontal curve, length of roadway section and number of through lanes. Chang (2005) used the number of lanes, lane width, horizontal curvature, and vertical grades. Sarhan (2008) included length of segment, lengths of acceleration and deceleration lanes, number of lanes, and weaving section types. In this study, more freeway characteristics are considered to evaluate geometric elements of the freeways leading to crash occurrence and provide appropriate recommendations. Two types of segments are considered in this study: EN-EX, and EX-EN. In every segment six models are develop to explain the two types of crashes: crash rate and severity crashes.

1.2 Statement of the problem

A freeway is considered as a major highway infrastructure designed to achieve high mobility and transitioning on and off urban streets through ramps. Currently, high frequency of crashes occurred on the freeway systems in Las Vegas, Nevada caused by more traffic weaving movements as a result of increased traffic. This is attributed to traffic flows competing at the limited spaces of the weaving sections on freeways. Drivers using these systems require more spaces available for appropriate decision making to avoid crashes. In the event that spaces between segment terminals is not sufficient, the likelihood of crash occurrence increases because drivers do not have time to observe and make decisions of avoiding crashes.

So far, models that were developed to quantify safety issues of geometric risk factors have evaluated EN-EX segment types (Liu et al., 2010; Golob et al., 2004; Sarhan et al., 2008). Little attention is given to detailed investigation of the effect of freeway geometric elements to crash rate and severity for EX-EN segment types. This proposed study will identify geometric design issues on freeway systems in Las Vegas, Nevada, based on available safety data for EN-EX and EX-EN segment types.

1.3 Research hypothesis

This study assumes that safety problems on freeway systems can be appropriately investigated by focusing on freeway segments between ramps. These segments are taken to be those located between the entry and exit to the terminals. Investigating geometrical elements on these segments will help understand the likely cause of crashes on freeways. One of the geometric elements assumed to cause crashes is the short length of segments defined by the space between entry and exit terminals. If the length on these segments is sufficient to allow drivers to observe and make decisions to avoid safety hazards, the likelihood of crash frequency occurring on the systems will be minimized.

Because of short lengths within these segments, it is further assumed that there are safety problems caused by vehicular traffic crossing each other for the purpose of either avoiding weaving vehicles or entering or exiting the facility. Segments involved in weaving movements are assumed to have geometric components which influence how movements are taking place and are likely to cause safety problems experienced within these segments. The geometrical configurations of entry to and exit from the main facility are likely to result in safety issues. Freeway segments which have auxiliary lanes to allow drivers to plan ahead and make decision to enter the facility are assumed to have better safety performance compared to those segments which do not have auxiliary lanes. Finally, it is also assumed that there is insufficient number of lanes to accommodate growing number of traffic on freeways and such a condition may likely cause crashes.

1.4 Objectives

Since safety issues are associated with geometric elements of freeway systems, the aim of the study was to investigate geometric design leading to safety problems. This was done by calibrating regression models to identify the geometric design factors that influence safety in the freeway systems in Las Vegas, Nevada. Different sets of regression models were developed for EN-EX and EX-EN segments. The developed models (crash rate models and crash severity models) were compared to identify the geometric problems. Solutions to mitigate the geometric design problems were proposed.

1.5 Organization of the report

There are six chapters included in this study. Problem statement, research hypothesis, study objectives and benefits are explained in Chapter 1. Chapter 2 reviews previous research activities specifically conducted on freeway systems including safety performance modeling approaches. Chapter 3 discusses study methodology where crash rate and severity model specifications are detailed. Data collection is described in Chapter 4. Chapter 5 discusses calibrated models and results of analysis. The solutions to mitigate the geometric design problems were presented in Chapter 6. Conclusions and recommendations are given in Chapter 7.

CHAPTER 2 LITERATURE REVIEW

This section reviews these characteristics with the main focus placed on safety performance of freeway geometric elements and statistical safety modeling approaches used in safety studies. The review is anticipated to provide a base in identifying safety problems specifically related to freeway systems, development of safety performance functions and recommends countermeasures to solve the identified problems.

Sarhan et al. (2008) conducted a study to evaluate the safety performance of freeways as influenced by the characteristics of speed-change lanes at the entrance and exit areas. Using data collected from 26 interchanges along highway 417 within the City of Ottawa, Ontario, Canada, the research group investigated the effects on collision frequencies occurred on the segments and on speed-change lanes of freeway geometric and operation features. Freeway geometric features included lengths of segments, acceleration and deceleration lanes as limited or extended lanes, number of lanes on the main facility, number of lanes of the two ramps bounding each segments and the type of weaving segments. Traffic volumes for main facility and at the entrance and exit ramps were also included. Using negative binomial modeling approach, the results indicated that increasing the lengths of both acceleration and deceleration lanes reduce crash frequencies as more time is available to motorists for correct decisions on merging and diverging tasks. Reduction in crash frequency was also true at locations where limited length of speed-change lanes was used compared to extended length. This implies that extended lanes are likely to be used as both acceleration and deceleration lanes which may increase the collision. It is also true that unfamiliar drivers may have impression that the number of lanes spans to both terminals, a situation which may subject them to risk factors.

They further investigated the effect on collision frequencies resulting from the type of weaving movements experienced on the weaving segments. Weaving movements were classified as Type A, where each weaving vehicle makes one lane change for successful completion of maneuver and Type B in which one of the two weaving maneuvers could be accomplished without making any lane change while a maximum of one lane-change is required by the other weaving vehicle. Modeling results indicated that weaving type A was safer compared to weaving type B.

The number and arrangement of lanes on freeway exit ramps also associated with safety performance of freeway diverge areas. For instance, Chen et al. (2009) used data collected on 343 freeway segments in the state of Florida to conduct an investigation on how the configurations of freeway exit ramps could affect their safety performance. In this case an observation unit was interpreted as a diverge area segments which contained a deceleration lane and an exit ramp which span distances of 1500 ft and 100 ft upstream and downstream of painted nose, respectively. Exit ramps were classified as single lane with tapered design (Type 1), single lane with outer lane of main facility dropped at the exit gore (Type 2), two-lane exit ramp with an optional lane to either exit or continue on the main facility (Type 3), and two-lane exit with an outer lane of the main facility dropped at the exit gore including a taper (Type 4). Crash frequency and rate as well as crash severity were investigated using t-test, proportionality test and regression analysis as statistical tools. Results of proportionality test indicated that the number and arrangement of lanes on freeway exit ramps does not affect crash severity in a significant way. Furthermore, the t-test indicated that Type 2 exit ramps (not lane-balanced) had significantly higher frequency and crash rates as compared to Type 1 exit ramps (lane-balanced). Also Type 4 exit ramps (not lane-balanced) had significantly higher crash frequency and crash rates as compared to Type 3 exit ramps (lane-balanced). This implied that using lane-balanced exit ramps improved safety performance at these areas. Regression analysis indicates that an increase in freeway AADT and ramp AADT, deceleration lane length increased number of crashes while increase in posted speed limit decreased crash counts. It was further shown that lane-balanced exit ramps had lower crash frequency compared to none lane-balanced exit ramps.

Chen et al. (2010) continued to investigate safety of freeway diverge areas by evaluating safety performance of left-side off-ramps. Specifically, the study examined the impacts of left-side off-ramps at the freeway diverging areas by using traffic conflict approach and evaluated the safety performance of the same areas by comparing with the right-side off-ramps. Further, the study identified the contributing factors to crashes at selected freeway segments. Using the same statistical approach, the results from the conflict approach showed that conflict rates at the locations with two exclusive off-ramps are slightly higher than the location with the optional lane. Cross-sectional comparisons showed that the left-side off-ramps have higher average crash counts, crash rates and percentage of severe crashes. A t-test indicated that only crash severity for left side exit ramps is significantly different with the right side diverge areas at selected freeway segments. A crash prediction model indicated that increasing freeway AADT, ramp AADT and length of deceleration lane would increase crash counts while increasing ramp length would reduce the potential crash counts for both left-side and right-side diverge areas.

Gore area is another location in freeway systems known to affect safety and operational performance of freeways especially when a driver is in its vicinity. It is described as a triangular piece of land found where roads merge or split and they are intended to help organize and protect traffic when cars are entering or exiting highway (Wikipedia 2013). When a driver approaches these areas, a large amount of directional information must be processed for a short period of time to avoid unpredictable maneuvers resulting from driver indecisiveness (FHWA-RD-97-095 1997). Lunenfeld (1993) showed that drivers increase the chance of making errors when they are to maneuver in the vicinity of the gore areas. Hakkert et al. (1998) showed that the use of bollard devices help to reduce erratic vehicle maneuvers at highway exits by 60% in daytime and up to 65% at night time.

Qi, et al. (2007) further conducted an investigation on geometric variables that were mainly located at the main facility. These included horizontal curvature, number of lanes, and length of roadway section. The study also included traffic flow defined as the hourly volume per lane and weather characteristics variables. Using data collected from Hampton roads, southeast Virginia, random effects ordered probit models were developed. Their results indicated that crash rates are very high at low levels of congestion, and decreases rapidly with increasing V/C ratio which then gradually increase at peak levels of congestion. The number of lanes was found significant. In the case of horizontal curve, the percentage of horizontal curve in a road section will affect the traffic accident likelihood with respect to unfamiliar drivers.

Chang (2005) considered numbers of lanes, lane width, horizontal curvature, vertical grade and AADT in their study. They developed Negative binomial and artificial neural network models, which indicated that an increase in the number of lanes increases accident likelihood because the total amount of lane changing as well as conflicts between traffic will increase. Freeway sections with grade equal to 3% or greater were found to increase the accident likelihood when compared to level sections. The results of horizontal curve showed that there is a reduction in accident likelihood with degree of curvature greater than six degrees. It was further revealed that the more closely interchanges are located, the more crash frequency is experienced. Lastly it was also indicated that as AADT increases, crash frequency is more likely to occur.

O'Cinneide (1998) is a study that reviewed the literature from different countries that dealt with the impacts of geometric design on roadway safety. The review included all types of roads and different geometric features. For example, it reviewed the study that investigated the impact of passing lane on two or three lane roads. It also reviewed the study on the impact of the number of lane on safety on two lane highways. It indicates that significant difference would result from modification of road alignments.

Realizing the tradeoff between access and safety by building an interchange between two interchanges, Pilko et al. (2007) investigated the characteristics of freeway segment, interchange to interchange, that influence safety. The characteristics considered in this study include interchange spacing, shoulder widths and number of lanes in the freeway segment. Measures for safety are total crashes and fatal and injury crashes happened in a freeway segment. The data for these characteristics and safety were collected from the states of California and Washington. Linear regression models were developed to correlate the safety and the characteristics of freeway segments. Sensitivity of the model was analyzed, and it was found that their models show a high sensitivity to freeway length and ramp AADT when predicting fatal and injury crashes.

The study in Park et al. (2009) focuses on the freeway segments that have curve and ramps. The freeway segments were not defined from interchange to interchange, or from ramp to ramp. They were selected only for those that have a curve with tangent before and after the curve. There may be ramps on some of the identified curves. These curves were on either rural or urban freeways. The geometric features identified for each curve includes number of lanes, median type, and density of ramps. The measure for safety is crash frequency. Negative binomial regress models were developed to relate the safety and the geometric features.

Golob et al. (2004) conducted a study on the safety implication of weaving sections on freeways. In their study, weaving sections were categorized into three types. Type A are weaving section where every merging or diverging vehicles must execute one lane change, Type B are those merging or diverging can be done without changing lanes, and Type C are those where one maneuver requires at least two lane changes. They used the data from Southern California. A multivariate Probit model was developed that relates the type of weaving section where an accident occurred and the characteristics of accident, the features of weaving section type, and traffic flow. It was found that there was no difference among these three types in terms of overall accident rates. However, there were significant differences in terms of the types of accidents that occur within these types in terms of severity, and location of the primary collision, the factors causing the accident, and the time period in which the accident is most likely to occur. We realized that Highway Capacity Manual has adopted a new categorization of weaving sections, which will be used in this study.

Ray et al. (2011) developed guidelines for ramp and interchange spacing, with emphasis given to ramp spacing. Safety is measured by number of crashes, crash types, and severity. Based on previous research, this study discusses the relationship between ramp spacing for the following three ramp combinations: EN-EX, EX-EN and EN-EN. Equations like Equation (1) to calculate crash frequency are provided for the ramp spacing combinations EN-EX and EN-EN.

$$Total = 9.7 * 10^{-6} L^{1.0} (DADT)^{1.12} (ADT_{EN})^{0.18} (ADT_{EN})^{0.02} exp\left(\frac{450}{s} - 0.23 * AuxLn\right) \quad (1)$$

"L" is segment length (in miles) defined from the physical gore of the first (upstream) entrance ramp to the end of the acceleration lane taper of the second (downstream) entrance ramp; "S" is ramp spacing (in feet) defined from the painted tip of the first entrance ramp to the painted tip of the second entrance ramp; "DADT" is the average daily traffic (in vehicles per day) on the freeway mainline upstream of the first entrance gore in the analysis direction; "(ADT_{EN})" – the first term is the average daily entering traffic (in vehicles per day) from the first entrance ramp; "(ADT_{EN})" – the second term is the average daily entering traffic (in vehicles per day) from the second entrance ramp; and "Total" is the number of crashes (of all types and severities) (crashes per year) expected to occur between the physical gore of the first (upstream) entrance ramp to the end of the acceleration lane taper of the second (downstream) entrance ramp. The variables in Equation (1) are specifically referred to in the ramp spacing in Figure 2.1

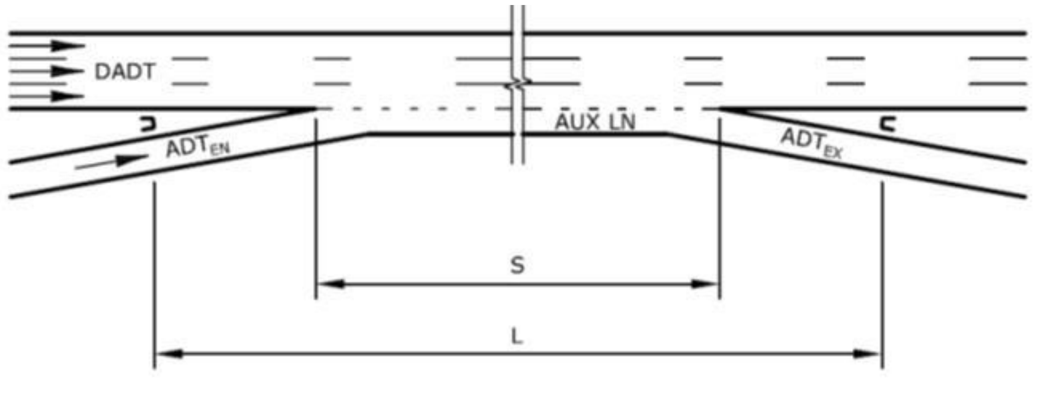


Figure 2.1: Typical Layout and Variables for the EN-EX Ramp Spacing Combination

Fitzpatrick et al., (2010) conducted a study to: (1) investigate relationships between weaving length, speed, and overall vehicle operations on Texas freeways; and (2) propose updates to current Texas Department of Transportation guidance on recommended distances between ramps. Microscopic traffic simulation models were calibrated for seven freeway locations. With the calibrated models, traffic volumes and length of weaving section were varied as inputs to the models. The data on weaving section length and traffic volumes from simulation models were then used to develop regression models to express weaving section length as a function of traffic volumes. The results from the regression models were used to develop guidelines on weaving section length in Texas.

Based on the literature review it can be summarized that different geometric features of freeway have been considered in different studies. Equations for safety in relation to different geometric features have been developed for adoption for planning, design and operations of freeway interchanges. These equations were not developed for individual states. To identify the geometric problems in Las Vegas, such equations should be developed based on the data from Las Vegas. Even though geometric features of freeways have been considered in these studies, they usually covered a few of them, not quite comprehensive. This study will consider all the major geometric features that describe the characteristics of freeways.

CHAPTER THREE METHODOLOGY

In this study, the geometric design issues on freeways in Las Vegas were investigated by following this process: literature review, methodology development, data collection, and data analysis. In literature review, the relevant studies conducted in the past were obtained from different sources and compiled with the identification of their study objectives, methods employed and the findings. The gap in identifying geometric design issues in the past was then revealed. Given the inputs from literature review, the methods to identify the geometric design needs are determined. The needed safety, geometric, operation and traffic data are then collected. These data were screened for quality control. They were analyzed based on descriptive statistics and used to develop crash rate and severity models. The results of the models were interpreted from which the geometric design needs of freeway were identified. To identify the specific segments that have geometric design problem, highway design experts in Las Vegas, Nevada were consulted, and their inputs, with the results from the regression models, were compiled. This process is presented in Figure 3.1.

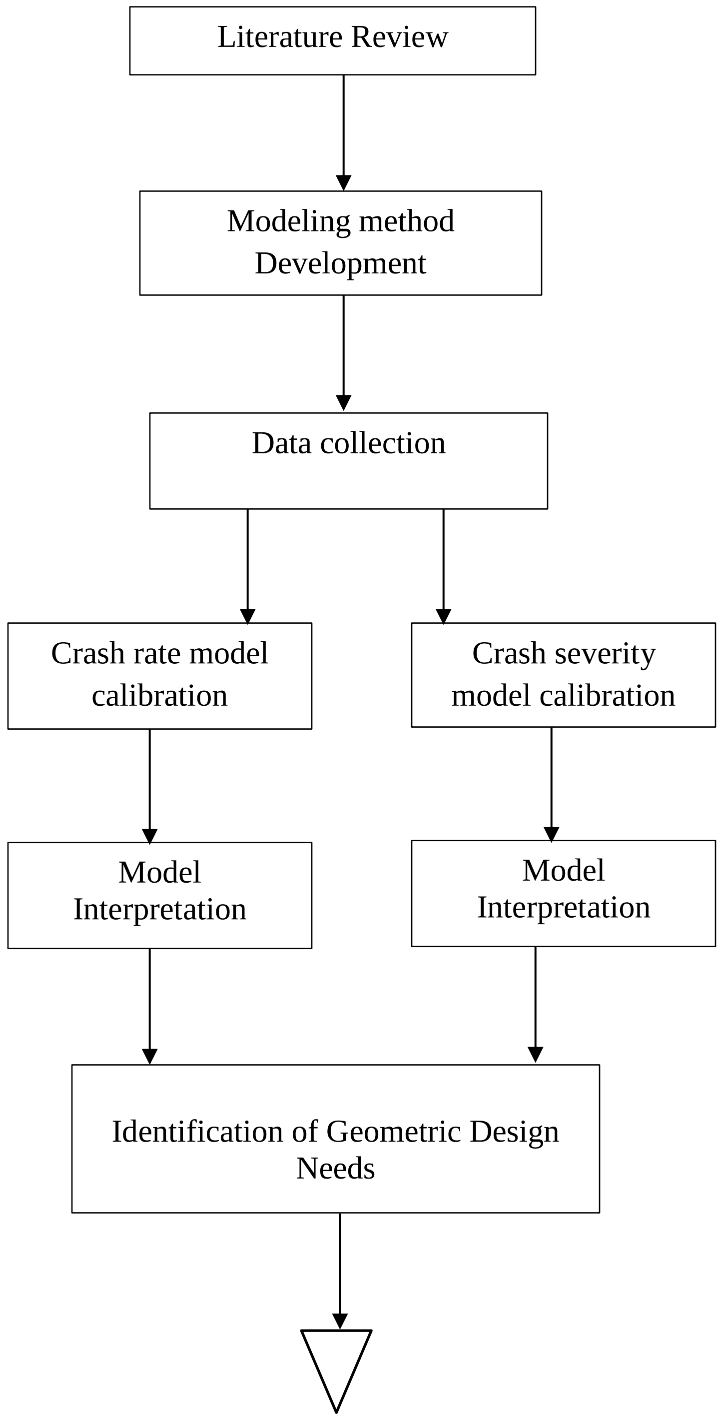


Figure 3.1: Research methodology

In this study, data for four segment types were collected: EN-EN, EX-EX, EN-EX, and EX-EN. Crash data include crash rate and crash severity. . Freeway characteristics data included length of segment, median and shoulder widths, number of through lanes, curve radius, grades, auxiliary lanes, number of lanes involved in weaving movements, AADT, and number of lane changes both from ramp-to-freeway and from freeway-to-ramp. Data analysis involves the quantitative description of data collected and the actual modeling of the data to quantify the relationship between freeway characteristics and crashes. Main features of data are described using descriptive statistics using graphs and summary statistics. To quantify the effects of freeway characteristics on crashes, statistical models are used. The following sections explain the statistical theory of the models for the type of crashes obtained.

3.1 Crash rate model

Crash rate is to measure the relative safety of a segment by combining crash frequency and vehicle exposure (FWHA 2013 and massDOT 2013). For the case of a road segment, crash rate can be calculated as:

$$R = \frac{100{,}000{,}000 \cdot C}{365 \cdot N \cdot V \cdot L} \tag{1}$$

where,

R = crash rate for the road segment expressed as crashes per 100 million vehicle-miles of travel (VMT)

C = Total number of crashes in the study period

N = Number of years of data

V = Number of vehicles per day

L = Length of roadway segment in miles.

The crash rate computed by equation (1) can be considered as a continuous outcome which is caused by freeway characteristics including (1) geometric elements of the freeway, (2) operation and traffic elements, and (3) weather related roadway travel pavement conditions. The relationship between a continuous outcome and freeway characteristics can be explained using multiple linear regression technique. Data are modeled using a linear function of freeway characteristics, whose values are used to predict the crash rate. The basic form of a linear function, y_i for data point y_i, and p freeway characteristics is given as:

$$y_i = \beta_0 + \beta_1 x_{i1} + \cdots \ldots \ldots \ldots \ldots .. + \beta_p x_{ip} + \varepsilon_i \tag{2}$$

where, $\beta_0 \ldots \ldots \ldots \ldots .., \beta_p$ are the unknown partial regression coefficients which indicate the relative effect of a particular freeway characteristic on the crash rate. y_i is the crash rate; x_i are freeway characteristics; ε_i is the error term which captures all other factors which influence the crash rate, other than the freeway characteristics in the model and it is assumed to be normally distributed.

The partial regression coefficients in equation (2) are estimated using ordinary least squares technique. The goodness of fit of the fitted regression model can be measured by using the sample coefficient of determination which gives the proportional or percentage of the total variation in the crash rate explained jointly by the freeway characteristics and it is given as:

$$R^2 = \frac{SST - SSE}{SST} \tag{3}$$

where, SST is the total sum of squares given as:

$$SST = \sum_i^n (y_i - \bar{y})^2 \tag{4}$$

SSE is the error sum of squares given as:

$$SSE = \sum_{i=1}^n (y_i - \widehat{y_i})^2 \tag{5}$$

The overall significant of the regression can be tested based on the assumption that none of the freeway characteristics has any linear relationship with the crash rate and it uses an F-statistic given as:

$$F = \frac{R^2/p}{(1-R^2)/(n-P-1)} \tag{6}$$

where,

R^2 = the coefficient of determination given by equation (3)

n = number of observations, and

p = number of freeway characteristics in the model.

Testing hypotheses about the insignificance of a population parameter at a given significant level uses a t test (Wooldridge 2009). The test about the influence of any population parameter uses individual partial regression coefficient and can be conducted by using a t statistic based on the regression coefficients and their standard errors as:

$$t_{\hat{\beta}_j} = \hat{\beta}_j / se(\hat{\beta}_j) \tag{7}$$

The coefficient is considered significant if the value in Equation (7) is greater than the critical value determined from the level of significance and the number of degrees of freedom. For this study, 5% level of significance is used.

3.2 Crash Severity Model

The analysis of crash severity examines the likelihood of different severity level of crashes such as property damage, injuries and fatalities. In the crash database, the crash severity is classified into one of the following three ordered categories: (1) property damage crash only, (2) Injury crashes, (3) Fatal crashes. The severity is ordered in nature, i.e., property damage crash is more severe than injury and fatal crashes. To model such ordered variables, usually ordered probit model is used.

An ordered probit model extends the probit model to multiple ordered categories where the numerical values of the categories do not matter, but categories must be in logical ascending or descending order. Different researchers have used the model to analyze crash severity in different areas of transportation and other fields (Gray et al. 2008, Zhu et al. 2011, Kockelman et al. 2002, Dykin et al. 2002, Abdel-Aty 2003, Yamamoto et al. 2008, and Shimamura et al. 2005).

The model is based on the assumption that the predicted crash severity $y_i{}^*$ depends linearly on the freeway characteristics according to the following equation:

$$y_i{}^* = x_i{}'\beta + \varepsilon_i \tag{8}$$

where $y_i{}^*$ is the predicted crash severity by driver i, β is a row vector of unknown parameters, x_i a vector of explanatory variables, and ε_i is the random error term that follows normal distribution. The severity level is classified based on the predicted severity using the following criteria:

$$y_i = \begin{cases} 0 & \text{if } y_i{}^* \le 0 \quad \text{(Property damage only)} \\ 1 & \text{if } 0 < y_i{}^* \le \mu_1 \text{ (Injury crash)} \\ 2 & \text{if } \mu_1 < y_i{}^* \le \mu_2 \text{ (Fatal crash)} \end{cases} \tag{9}$$

y_i in Equation (9) represents observed severity levels ("0" for property damage, "1" for injury crash, and "2" for fatal crash); $\mu 1$, $\mu 2$ and $\mu 3$ are the thresholds estimated by the model.
The estimated coefficients on the explanatory variables capture the marginal effect of the corresponding factor on the injury severity of the crash. In this case, a positive value of a coefficient indicates that the corresponding explanatory factor is associated with higher severe crashes (Zhu, et al., 2011).

The probability that the severity of a crash i is equal to y_i is written as:

$$P(y_i = 0|x_i) = \Phi(\mu_1 - \beta x_i) \tag{10}$$
$$P(y_i = 1|x_i) = \Phi(\mu_2 - \beta x_i) - \Phi(\mu_1 - \beta x_i) \tag{11}$$
$$P(y_i = 2|x_i) = 1 - \Phi(\mu_2 - \beta x_i) \tag{12}$$

In Equations (10), (11), and (12), $\Phi(.)$ is the standard normal cumulative distribution function. The log-likelihood function of a crash being any severity is given as:

$$\log L = \sum_i \ln[P(y_i)] \tag{13}$$

The coefficients β_j are computed in such a way they maximize the log-likelihood function indicated by Equation (13). The overall significance of the explanatory variables is tested by comparing the restricted log-likelihood ($Log\ L_R$) to the maximized log-likelihood ($Log\ L_U$) to produce the likelihood ratio test statistic given as:

$$LR = -2(Log\ L_R) - Log\ L_U) \tag{14}$$

This statistic is distributed as χ^2 with degrees of freedom equal to the number of explanatory variables. The test is based on the null hypothesis that none of the explanatory variables have an effect.

For the analysis of data with ordered probit model, an equivalent statistic to R^2 does not exist because the model are maximum likelihood estimates arrived at through an iterative process (UCLA 2013). In this study, the goodness-of-fit of the model is evaluated using McFadden's Pseudo statistic given as:

$$Pseudo - R^2 = 1 - \frac{Log\ L_U}{Log\ L_R} \tag{15}$$

where $Log\ L_R$ is the log-likelihood of the intercept model treated as a total sum of squares, and $Log\ L_U$ is the log-likelihood of the model treated as the sum of squared errors. A small ratio of the log-likelihoods indicates that the full model is as far better fit than the intercept model.

CHAPTER 4 DATA COLLECTION

Data used were collected from three freeways located in Las Vegas, Nevada (see Figure 4.1) which included: I-15, I-215, and US 95. These freeways were divided into contiguous segments of freeways bounded by entry and exit. Table 4.1 shows that the numbers of segments for US 95 and I-215 considered in this study are more than that for I-15. For each segment, four groups of data were collected: (1) geometric, (2) operation (3) traffic data and (4) environmental. Geometric data included length of segments, shoulder and median widths, number of through lanes, auxiliary lanes, segment terminal configurations, curve radius, and grades. Operation data are for weaving movements which were also collected as a function of geometric characteristics affecting these movements and these included: number of lanes involved in weaving movements, number of lane changes from ramp-to-freeway, and number of lane changes from freeway-to-ramp. Environmental data included pavement surface denoted whether a pavement was wet or dry at the time a crash occurred.

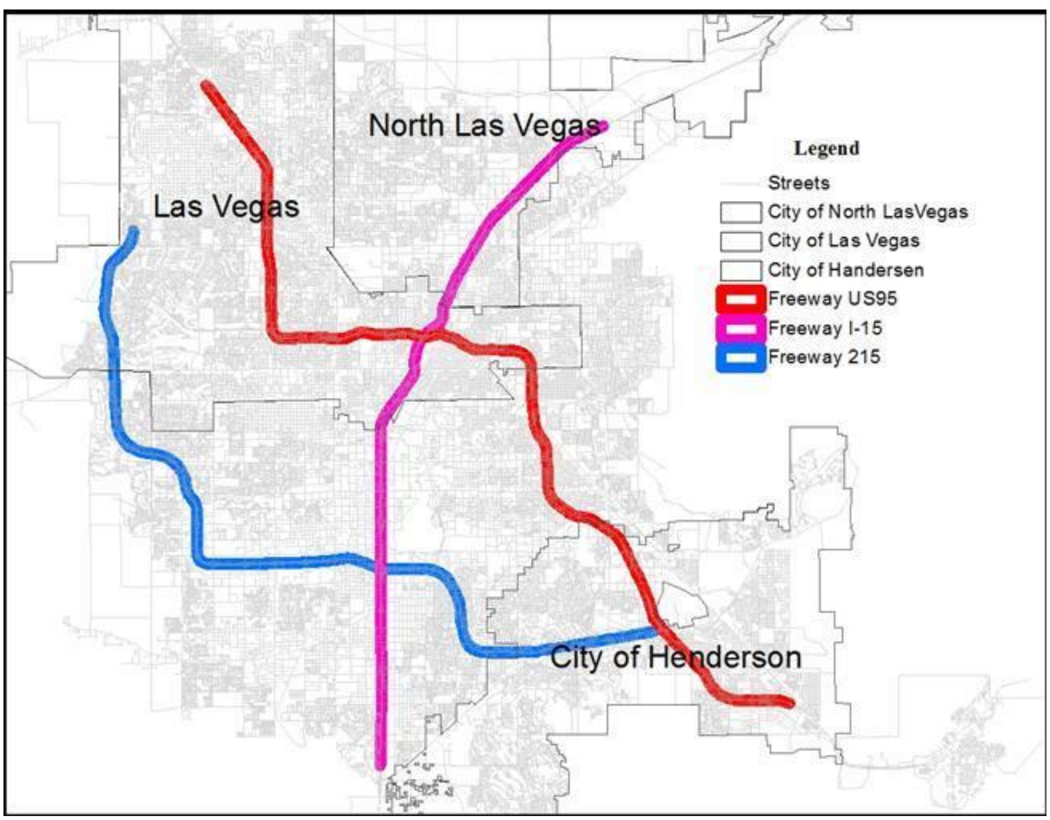


Figure 4.1: Study location

Table 4.1: Total segments in each freeway

Freeway	Number of segments
I-15	73
I-215	104
US-95	116

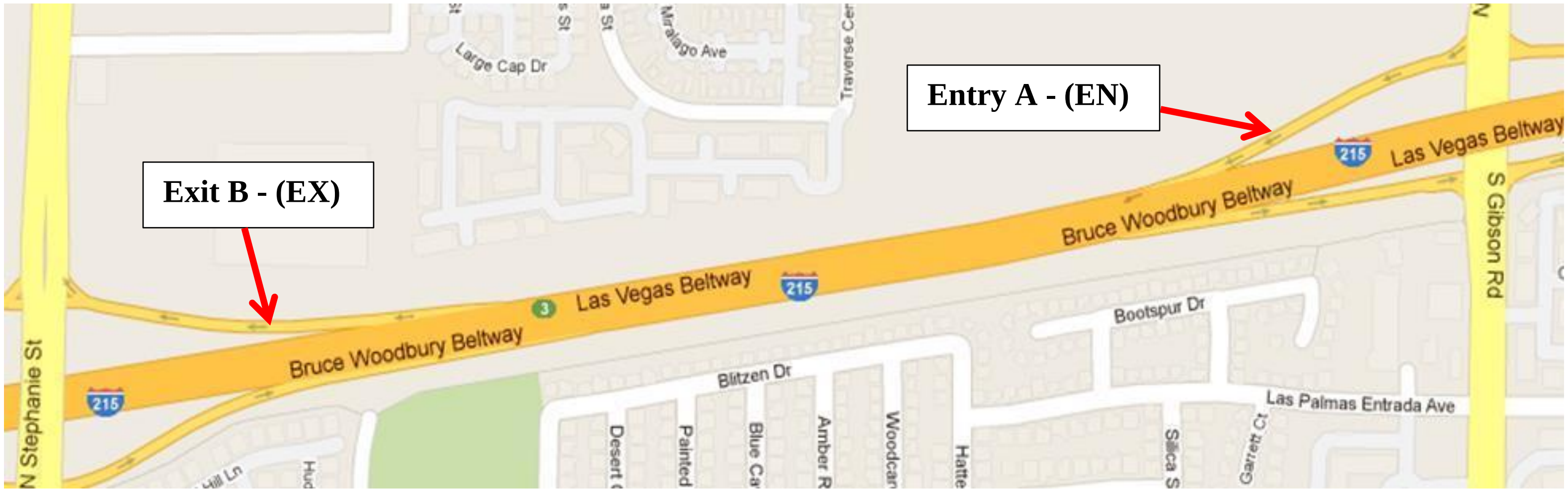


Figure 4.2: EN-EX Segment (bounded by entry A and exit B)

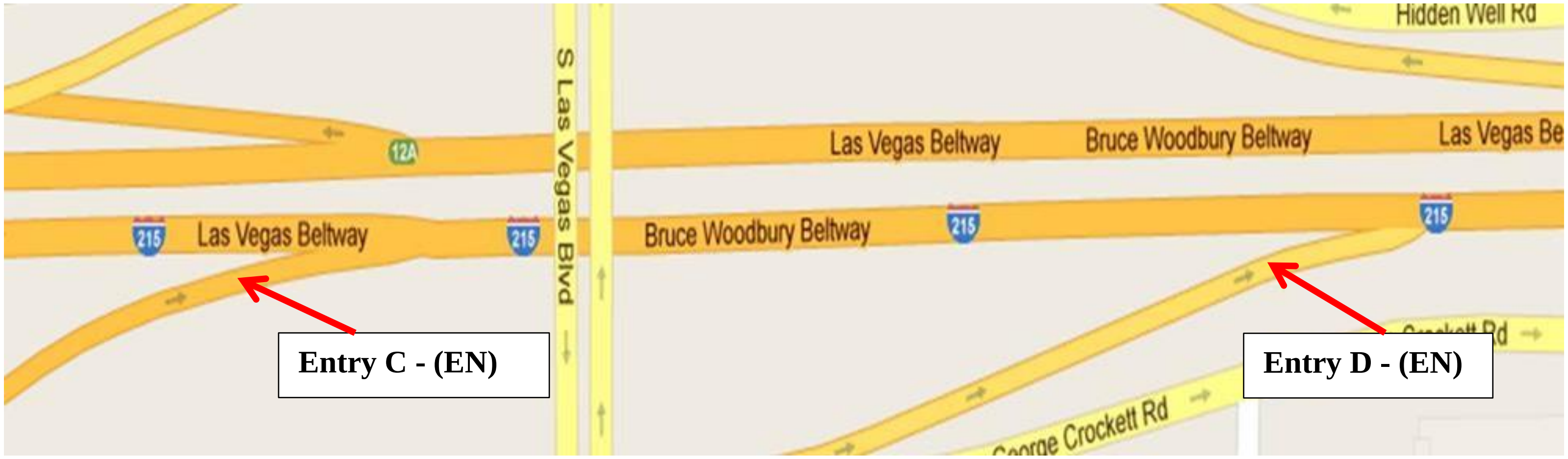


Figure 4.3: EN-EN Segment (bounded by entries C and D)

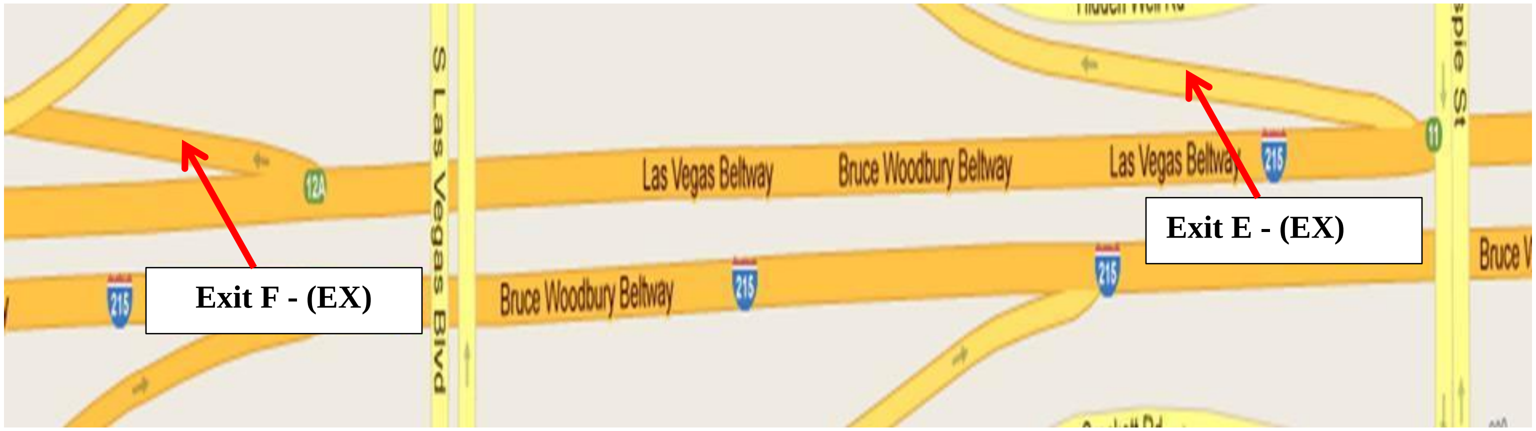


Figure 4.4: EX-EX Segment (bounded by exits E and F)

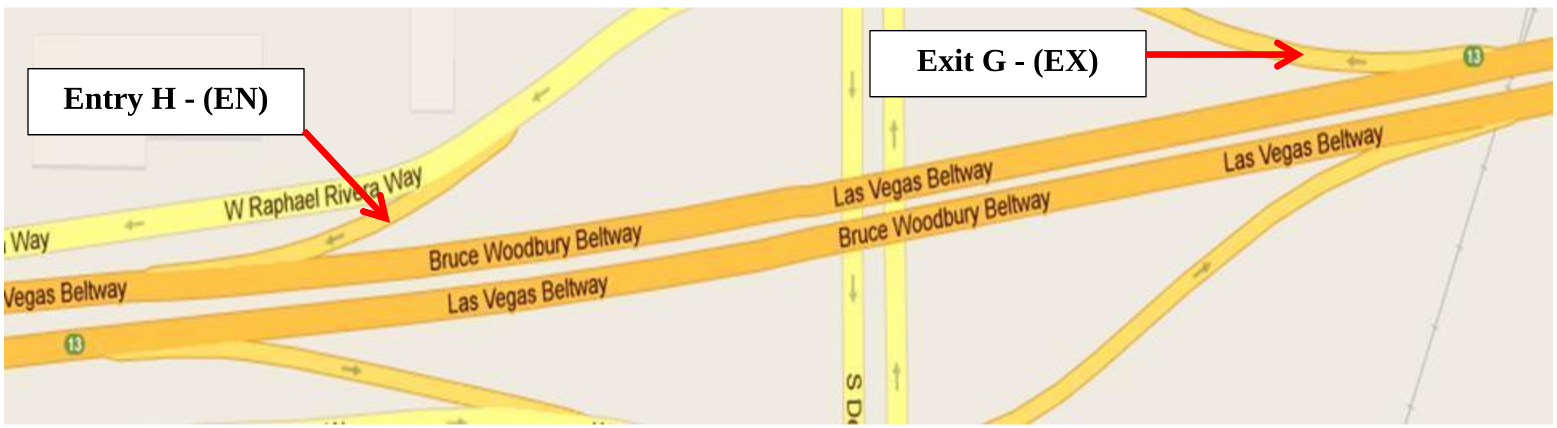


Figure 4.5: EX-EX Segment (bounded by exit G and entry H)

Segmentation

Figures 4.2 to 4.5 show four types of segments observed as defined by their terminal configurations. These constituted observation unit. Geometric elements of freeways were observed and recorded from each segment. Crash data, posted speed limit and pavement surface environmental conditions were obtained as an Excel file from Nevada Department of Transportation. Using latitude and longitude of the crash data, the file were converted to a point shapefile and overlaid with the created segment polygon. However, Crash data file provided by NDOT contains crash location that seems to follow shapefile from 2007. Coordinates given might not be projected at the exact location where crashes had occurred. The point features created from spreadsheet show crash data points in a straight line that follow Clark County street center lines shapefile. The similarities can be seen in screen shots below (Figure 4.6) in which the Google Earth image dated 2007 has same freeway (95 and Decatur) diverging construction area which matches the ArcGIS crash points along street centerline.

Figure 4.6: Overlay problems of crashes and segments

The projected crashes where not overlaid exactly on the segment polygons created and spatial adjustment was applied (Gorr et al. 2011). Figure 4.7 shows segment polygons with crashes overlaid. Crash frequency was obtained by joining the point and polygon shapefiles. Using appropriate tools in GIS, crashes happened in the polygon are counted and the results exported to Excel files which were then cleaned to obtain the final required crash frequency. Cleaning involved removing all variables created under the process of counting for instance crash number, vehicle and street directions.

Crash severity data were also obtained by overlaying the crashes with polygon shapefiles. Crashes falling in an individual segment were visualized and recorded in the same way as for the frequency data, and the resulting data were exported to the Excel file for data cleaning. The data exported to the Excel file include many data items. Not all the data items were needed in the modeling process, for instance codes indicating street directions, driver actions, crash number, and city towns. This information was removed as a process to clean the dataset. The speed limit and travel way surface conditions were also extracted from the crash data file obtained from Nevada Department of Transportation.

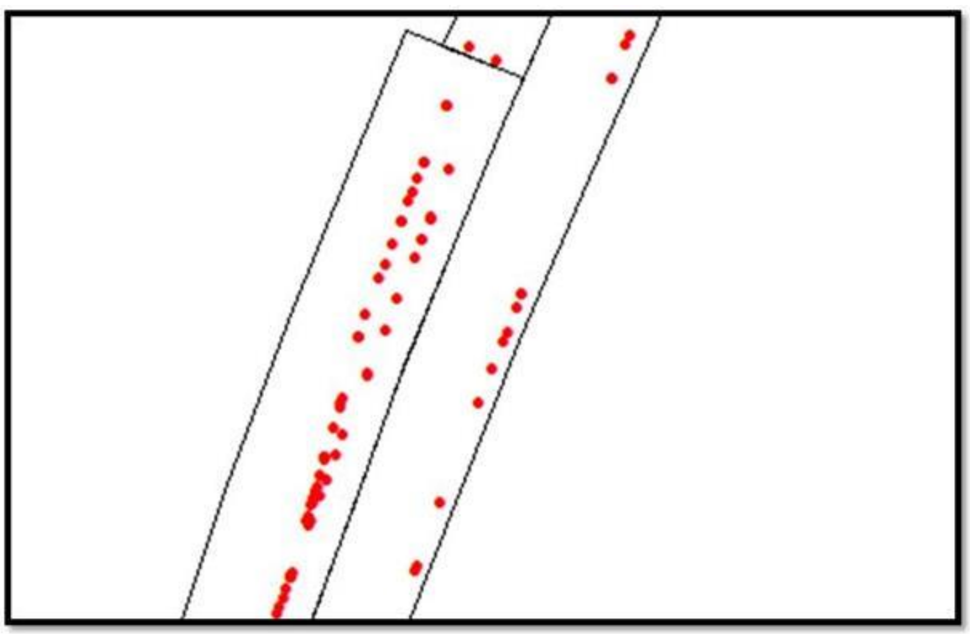


Figure 4.7: Crashes overlaid with digitized segments

Geometric data

Length of each segment was defined as the base length (L_B) between its terminals as defined in 2010 Highway Capacity Manual and in Roess et al. ((2011) which is shown in Figure 4.8. The width of each segment was taken as equal to the width of a freeway define by the number of through lanes plus the inside median and outside shoulder widths (Figure 4.9). This helped include all crashes occurred on the main facility, speed-change lanes, and those found on median and shoulders.

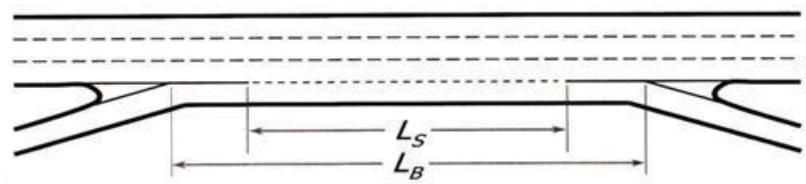


Figure 4.8: Definition of length of segment (Source: HCM2010)

Figure 4.9: Sample segment digitized showing the measurements of segment width

It is shown in Figure 4.10 that shoulder width was taken as the ground length measured from the point where edges of the external lanes touch the shoulder to the point where it ends at pavement edge. The median width was taken as the ground length from the point where the extreme inside lane touches the median to the center of the median on each direction of the freeway. This width included the inside shoulder. Both median and shoulders were measured using available tools in the Google Earth Pro Imagery of 2010. Figure 4.10 illustrates the measurement of these variables.

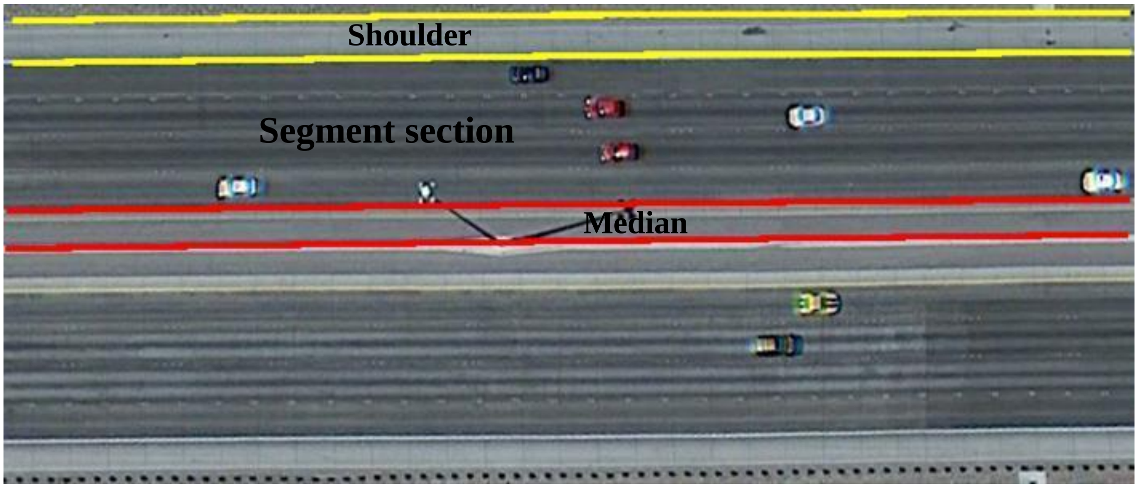


Figure 4.10: Median and shoulder width – ground distance between the two red lines

The number of through lanes were visualized and counted using Google earth as the number of marked mainline on the freeway which delineate lanes of travel. For segments where the auxiliary lane extends from entrance to exit, the auxiliary lane was included in the total number of through lanes (Sarhan et al., 2008).

Figure 4.11: Part of a segment indicating through lanes

The types of auxiliary lanes included are continuous auxiliary lanes. These are portion of the roadway adjoining the traveled way for speed change, turning, weaving, truck climbing, maneuvering of entering and leaving traffic. Their purpose is to supplement through-traffic movement and improve operational efficiency (AASHTO 2001)

Vertical and horizontal alignments are not reported in any database for the state of Nevada. Grade for freeway segments was recorded from Google Earth pro using the average grade technique (Roess 2011). This approach is acceptable for freeway segments containing composite grades with segment lengths less than 4,000 feet and grades less than 5%. Freeway segment elevations were recorded from Google Earth at the painted gore nose of each terminal on either side of the segment. The difference of the two elevations was divide by the segment length resulting in the calculated average grade and used as a variable in the modeling as the average grade for that segment. Google Earth provides the ability to produce alignment grade by creating a path in order to generate a profile. However, most freeway segments have multiple grade changes which cause uncertainty with collecting either the maximum grade of the freeway segment or to record the average. One study suggests the use of global positioning systems (GPS) to collect roadway alignment (Awuah-Baffour et al. 1997). We did not take this GPS approach because the fore mentioned study was not concerned with the use of the data but just the accuracy of the data collection.

In this study, each curve observed on each segment from Google Earth was treated as a simple curve, and the radii were determined using ArcGIS Curve Calculator under the COGO toolbar. The arc length was measured in ArcGIS, along with the chord length. With those two measurements, the freeway segment radii were determined with the use of the calculator. Some segments shared the same curve radius due to curve length surpassing the designated segmentation of painted gore to painted gore. When a segment contained more than one curve, the shorter radius was taken having the most extreme effect on vehicle maneuvering. An example can be seen in Figure 4.12. Such was the case for freeway segments containing part of a curve and no curve for the reminder.

Figure 4.12: Reverse curve located on US 95 and Russell Rd interchange, curve with smaller radius circled

More complicated curves such as spiral and combination curves, similar to the reverse curve seen in Figure 4.12, could not be determined based on visual inspection. There are a few methods exist for recording curve radius. According to one method, researchers suggest using ArcGIS to dissolve polyline vertices into those segment vertices with drastic changes in order to analyze less coordinates (Hans et al. 2012). Then the resulting coordinates are used to iterate chord lengths which are then analyzed through regression. This method was proven to be the most accurate but may be too time consuming. Thus it was not adopted for this study.

Operation data

On EN-EX segments where merging movements are closely followed by diverging segments, there is insufficient distance for merge and diverge segments to operate independently. This situation necessitate traffic streams to cross each other because drivers entering and exiting the facility need to locate themselves to their desired lanes for either continuing travel along the facility or exiting the facility. Segments of the facility from which an additional weaving movements are taking place by lane–changing activity are called weaving segments. These segments have geometric components which influence how movements are taking place and are likely to cause safety problems experienced within these segments. To present the traffic situations on these segments, three data items were collected: lane change from ramp-to-freeway, lane change from freeway-to-ramp, and number of lanes involved in weaving movements (see Figures 4.13 and 4.14). These data items are defined in the 2010 Highway Capacity Manual. From a segment like the one on Figure 4.13, it is assumed that every weaving vehicle enters the segment in the lane closest to its desired exit and leaves the segment in the lane closest to its entry. The number of lane change in Figure 4.13 is one. The second data item involved the minimum number of lanes involved for successively completing the lane changes. Since a vehicle moves from the auxiliary lane to the lane closest to the next exit terminal, only two lanes are involved to successively complete the movement.

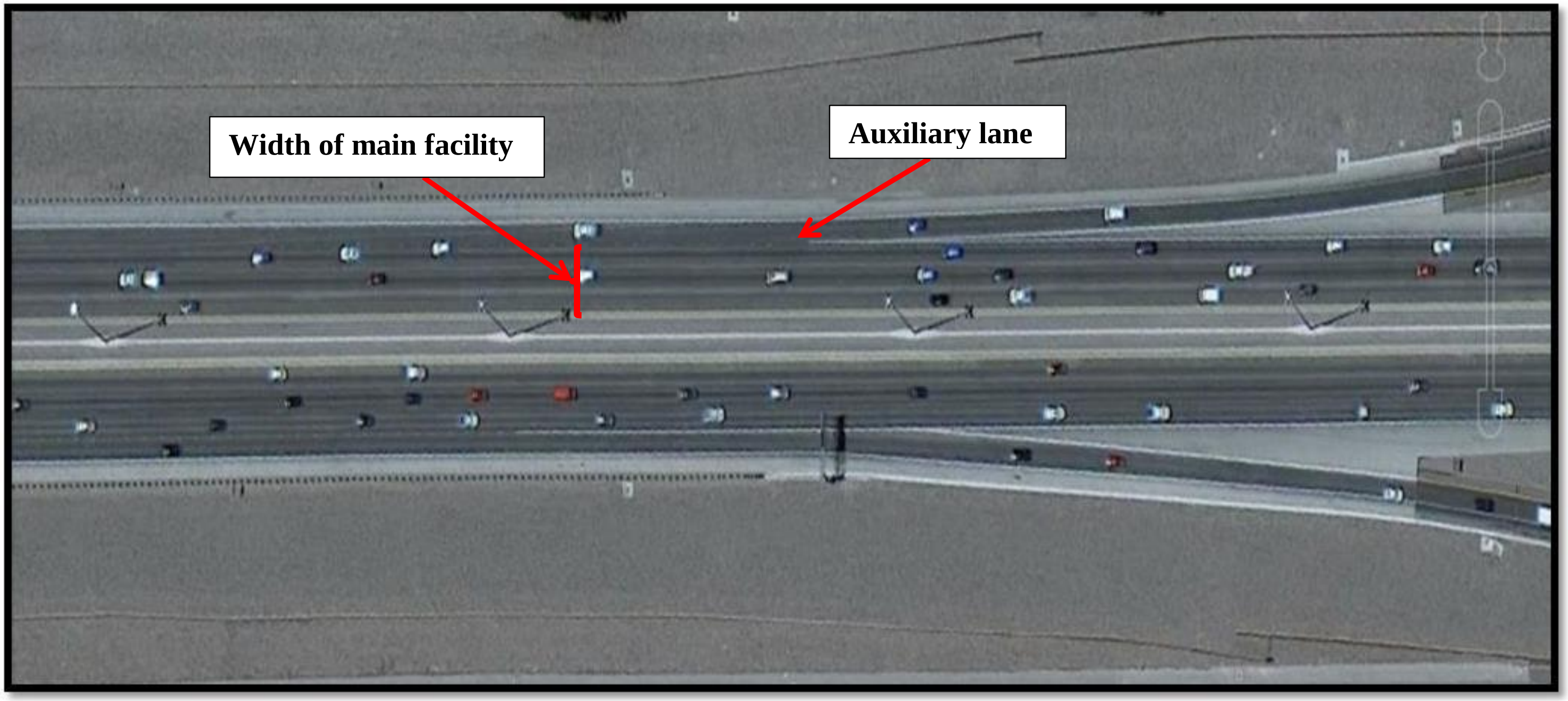


Figure 4.13: Weaving movement variables - lane change from ramp-to-freeway and weaving movement lanes

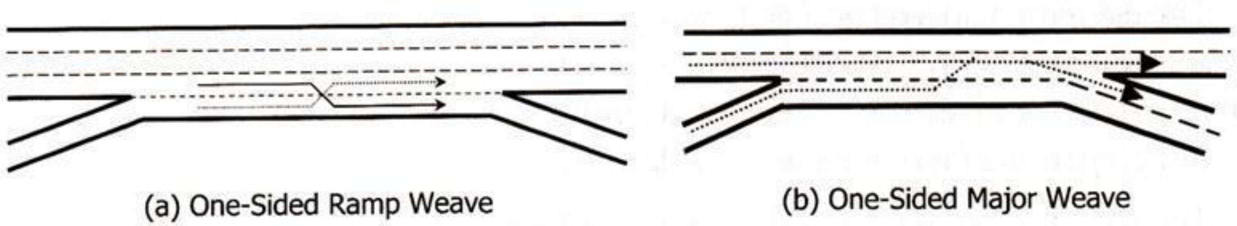


Figure 4.14: One-sided weaving segments (Source: HCM2010)

<u>Traffic volume and speed limit data</u>

Traffic and control data involved speed limit and average annual daily traffic data (AADT). Average annual daily traffic data were provided by the Nevada Department of Transportation (NDOT), given in their recent report for Clark County NDOT (2012). NDOT reported actual vehicle counts and estimated values for 2010. Although counts were not provided for each segment location, further evaluation for missing segment volumes was needed. For the segments requiring additional analysis, a balanced approach was taken to determine traffic volumes for each location using ramp volumes and nearby count locations provided. This approach is demonstrated in Figure 4.15 where the sum of the given volumes 126,000 vehicles per day for mainline flow is calculated with 15,000 and 12,000 for on-ramp and off-ramp, respectively. The resulting AADT of 153,000 vehicles per was taken for the segment of US 95 south of Craig Road.

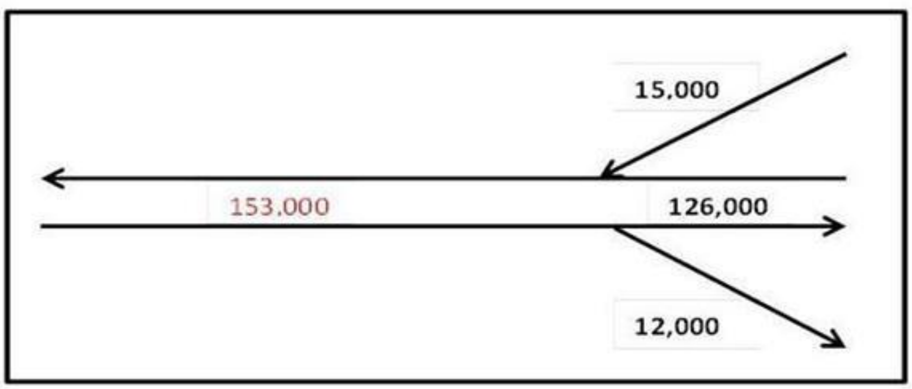


Figure 4.15: Balanced approach example, calculated output value in red

For segment volumes that could not be determined through this approach due to vague location description in the traffic report, the AADT value of the nearest location was assigned. Only a few segments were handled in this manner which can be seen in Figure 4.16.

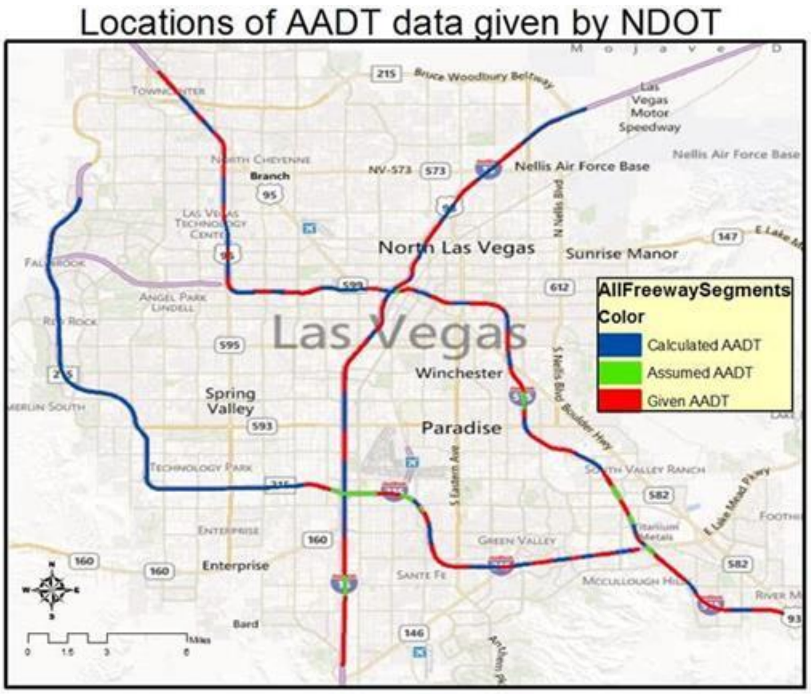


Figure 4.16: Comparative map of given AADT locations calculated

CHAPTER 5 MODELING RESULTS

5.1 Descriptive statistics

This study used data collected from freeways I-15, I-215 and US95 to investigate possible factors contributing to crashes. Four segment types were observed: EN-EX, EX-EN, EN-EN, and EX-EX. For the selected analysis year, active work zones were observed for some of the segments and these segments were excluded from the analysis. Table 5.1 indicates number of segment types and total crashes per segment type per freeway. The table also indicates the presence of small number of segments for EN-EN and EX-EX and these segment types were also excluded from the analysis due to small sample size. Calibrated model results shown on section 5.2 and 5.3 involved a total of 249 segments of type EN-EX and EX-EN. Table 5.2 indicates number of type of crashes in every freeway which occurred in the analysis year.

Table 5.1: Number of segment types and crashes in every freeway

	# of segments			**# of crashes**		
Segment type	**I-215**	**I-15**	**US 95**	**I-215**	**I-15**	**US 95**
EN-EX	48	24	34	78	131	115
EX-EN	47	23	32	187	109	162
EN-EN	2	9	11	0	8	38
EX-EX	3	6	9	20	21	23
Total	100	62	86	285	269	338

Table 5.2: Summary of crash types in every freeway

	I-215		**I-15**		**US95**	
Segment type	IC	PD	IC	PD	IC	PD
EN-EX	21	57	45	86	44	71
EX-EN	58	128	29	80	55	107

Key: IC: Injury crashes; PD: Property damage

Table 5.3 indicates a two dimension categorization of segments for part of the data from Table 5.1 according to the segment type by freeway. A chi-square test indicates that observed pattern of frequencies of crashes differ in overall for every freeway per segment type. This result indicates the existence of risk factors leading to different safety performance of these segment types. Table 5.3 aggregates type of crashes as indicated on Table 5.2. Relating individual crash type with geometric elements in every segment complements results indicated by the chi-square test and this explains what factors are attributed to the occurrence of crashes. This is covered in section 5.3

Table 5.3: Comparison of proportional of crashes per segment type per freeway

	Total crashes			
Segment type	**I-215**	**I-15**	**US 95**	**Total**
EN-EX	78	131	115	324
EX-EN	187	109	162	458
Total	265	240	277	782
Pearson chi2(2) = 32.8276 ; Pr = 0.000				
Likelihood-ratio chi2(2) = 33.1500 ; Pr = 0.000				

Table 5.4 and 5.5 summarize descriptive statistics for geometric elements observed in EN-EX and EX-EN segment types. Figures 5.1 and 5.2 below supplement results on Table 5.4 to indicate crash rate distribution with individual freeway characteristics.

Table 5.4: Descriptive statistics of variables for EN-EX and EX-EN segment types

EN-EX segments

Variable	I-215				I-15				US95			
	Mean	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**
2010 crash rate	0.159	0.488	0.000	3.301	0.193	0.299	0.000	1.415	0.145	0.243	0.000	1.179
Through lanes	3.85	0.46	3	5	3.79	1.18	2	6	3.29	0.87	2	6
Radius curve (ft)	4473.3	1581.2	950.2	7418.8	4707.1	2437.9	1247.0	9958.2	3485.6	1052.3	1811.2	5848.8
Shoulder width (ft)	12.14	1.18	10.04	13.96	11.89	1.21	10.01	14.02	11.69	2.37	6.30	19.90
Median width (ft)	14.33	1.94	3.66	16.71	15.70	1.98	12.07	19.17	8.72	2.30	3.40	13.20
Length (m)	802.47	407.84	233.87	1825.93	1076.12	788.28	243.00	4303.45	1225.4	628.7	158.5	2635.9
AADT	142335	63625	28300	291600	154671	87635	25500	298100	135677	62950	27000	283000
Total segments	**48**				**24**				**34**			

EX-EN segments

Variable	I-215				I-15				US95			
	Mean	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**
2010 crash rate	0.223	0.346	0.000	1.364	0.145	0.293	0.000	1.144	0.156	0.292	0.000	1.316
Through lanes	3.00	0.21	2	4	3.72	1.27	2	5	3.06	0.62	2	5
Radius curve (ft)	4145.2	1531.5	1811.2	7608.1	3918.8	2355.0	501.7	9930.4	3810.9	2111.1	507.4	9930.4
Shoulder width (ft)	12.16	1.07	10.14	14.87	12.06	1.03	10.27	13.92	12.48	2.51	8.20	18.90
Median width (ft)	14.83	1.12	12.65	16.82	16.41	1.62	13.37	18.78	9.09	2.76	2.90	14.70
Length (m)	1027.6	309.5	390.8	2116.4	1100.9	556.4	348.9	2222.1	912.4	331.9	272.2	1881.5
AADT	140092	67349	25500	298100	149648	86503	25500	291600	133253	52117	44500	246000
Total segments	**47**				**23**				**32**			

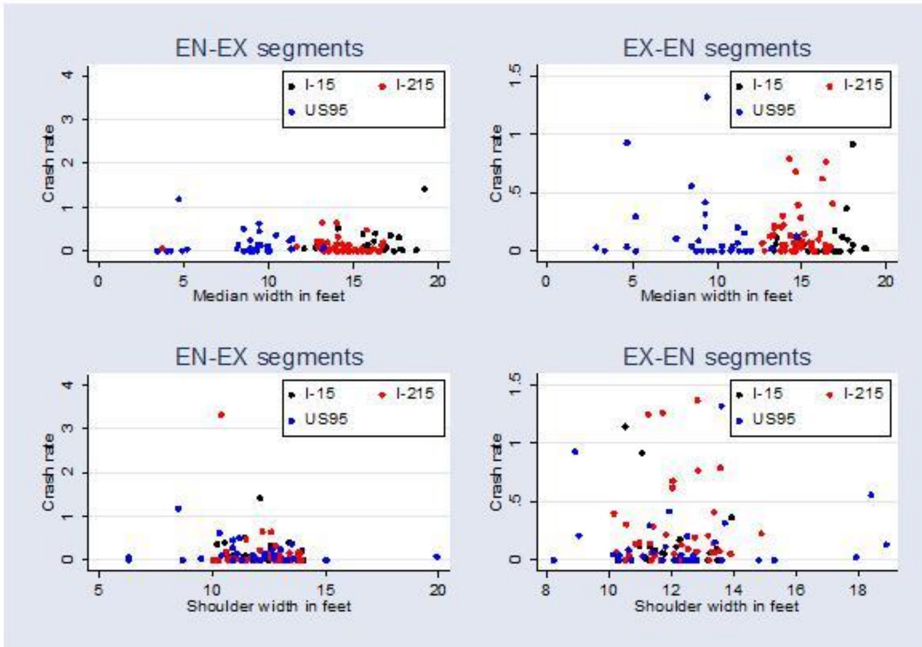


Figure 5.1: Distribution of crash rate against median and shoulder widths across segment types

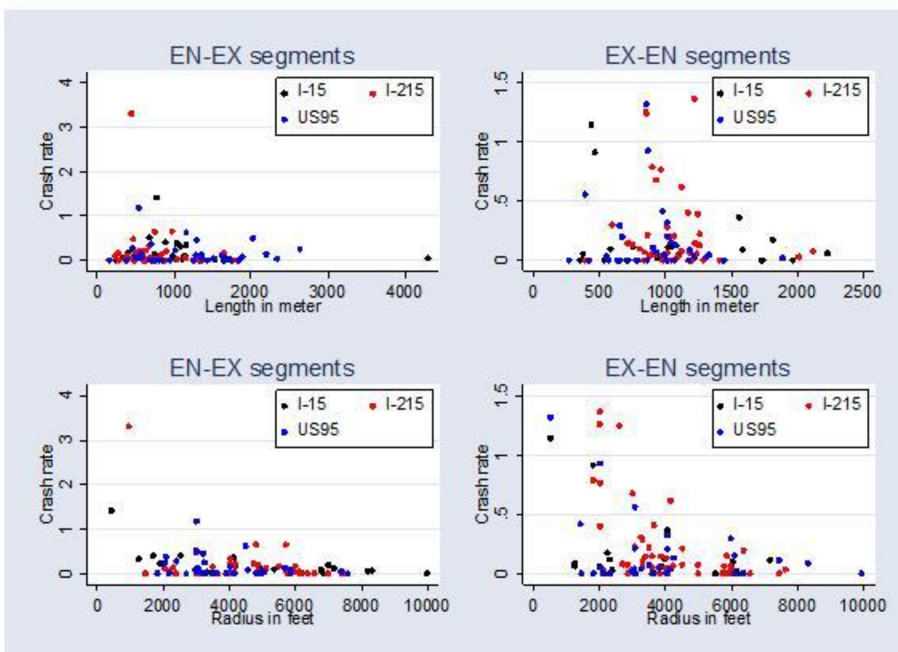


Figure 5.2: Distribution of crash rate against length and radius across segment types

Figure 5.1 above presents the distribution of crash rate across median and shoulder widths for EN-EX and EX-EN segment types. Comparing the medians of EN-EX and EX-EN segments, the figure indicates that I-15 and I-215 have wider medians than US 95. Also the crash rate is higher for EX-EN segments compared to EN-EX segments. For EX-EN segments, there are higher crash rate for narrower shoulders than for EN-EX segments.

Figure 5.2 presents the distribution of crash rate across segment length and radius of curve. The figure shows that there are higher crash rate for EX-EN segments with relatively low segment length and radius of curve than EN-EX segments. Furthermore, EN-EX segments on I-15, I-215, and US 95 have short lengths while these values are sparse for EX-EN segments

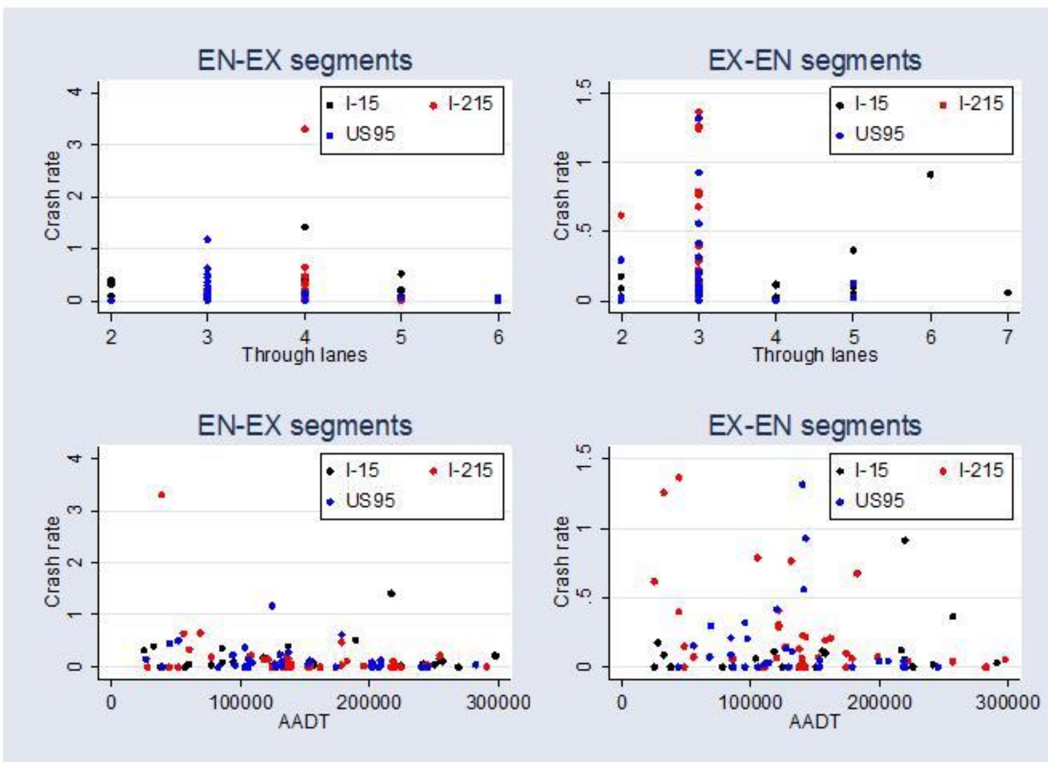


Figure 5.3: Distribution of crash rate against through lanes and AADT across segment types

Figure 5.3 presents the distribution of crash rate across the number of through lanes and traffic volume. EX-EN indicates higher crash rate at low values of number of through lane compared to EN-EX segments. However, crash rate decreases with more through lanes.

In general, observed freeway characteristics as summarized in Tables 5.4 and their corresponding graphical presentations in Figures 5.1, 5.2, and 5.3 indicates that safety performance of EN-EX and EX-EN segments seems to be a function of their geometric elements observed on those segment types. The quantification of their impact on crash rate can be investigated by calibrating a model relating crash rate and geometric characteristics and this is discussed in section 5.2.

5.2 Crash rate model

Table 5.6 presents the results of crash rate model estimated using Stata software (2008). As indicated by the test of exclusion restrictions and corresponding p-values, all predictors included in the models have an overall impact to crash rates. The models also indicate that predictors in EN-EX segment types on I-15 explained the highest percentage of crash rate variations. For EX-EN segment type I-215 was observed to explain the highest percentage.

EN-EX segment on I-15: The results in Table 5.5 indicated that more lanes increased average crash rate as shown by the positive coefficient on the number of through lanes. This might be due to the fact that, segments with more lanes influences driver behavior of maneuverability such as lane changes which may lead to sideswipe and angle crashes. In cases where there are high traffic volumes and high percentage of trucks in the facility, overtaking vehicles are susceptible to rear-end chain reaction crashes. The coefficient on the radius of curve is negative which implies that segments with large radius reduced average crash rate. This might be that large radius provide better visibility for drivers negotiating curves to avoid encountered risk factors. Wide shoulders and medians have a negative impact on I-15. This is shown by the negative coefficient on both shoulder and median width. Wider medians and shoulders are expected to provide more spaces for emergency storage of disable vehicles which reduce the risk of rear-end crashes. Also drivers can easily maneuver to avoid crashes or more spaces used as a recovery area for drivers who have left the travel lane.

Table 5.5: Crash Rate Model Results

Variable	I-15			I-215			US 95		
EN-EX segment type									
	Coef.	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**
Through lanes	0.071	0.034	2.120	-0.406	0.117	-3.470			
Log (Radius of curve)	-0.180	0.063	-2.870	-0.296	0.115	-2.580	-0.302	0.107	-2.820
Log (Shoulder width)	-1.445	0.538	-2.680	-1.913	0.556	-3.440	-0.334	0.103	-3.230
Log (Median width)	-2.057	0.546	-3.770	-0.854	0.186	-4.600			
Log (Length)				-0.265	0.103	-2.590			
Constant	10.552	1.547	6.820	12.900	1.826	7.060	3.378	0.843	4.010
Auxilliary statistics									
R-Sq.	0.7332			0.6235			0.4407		
Adj. R-Sq	0.6770			0.5787			0.4047		
F statistics (p-value)	13.05 (0.000)			13.91 (0.000)			12.22 (0.000)		
Number of segments	24			48			34		
EX-EN segment type									
	I-15			**I-215**			**US 95**		
Variable	**Coef.**	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**
Through lanes	0.076	0.035	2.2	-0.584	0.226	-2.590			
Log (Radius of curve)	-0.189	0.063	-3.02	-0.350	0.081	-4.330	-0.219	0.101	-2.170
Log (Shoulder width)	-1.263	0.525	-2.4	-0.400	0.155	-2.580	-1.054	0.170	-6.210
Log (Median width)				-0.328	0.109	-3.000			
Log (AADT)				0.143	0.066	2.160			
Constant	4.4554	1.327	3.36	3.846	1.160	3.310	4.554	0.756	6.020
Auxilliary statistics									
R-Sq.	0.5933			0.7323			0.6868		
Adj. R-Sq	0.5291			0.6997			0.6652		
F statistics (p-value)	9.24 (0.0006)			22.43 (0.000)			31.80 (0.000)		
Number of segments	23			47			32		

EN-EX segment types on I-215: The impact of through lane on I-215 negative, more lanes reduced the average crash rates as indicated by the negative coefficient on the number of through lanes. This might be because with more lanes space is available for drivers to maneuver and avoid crashes as well as there is an improved capacity of the freeways. This observation is different from that for the segments on I-15, and is worthwhile for further investigation. Other geometric variables all have negative signs, the same as those for the EN-EX segments on I-15. The coefficient on segment length is negative which implies that long crashes reduced average crash rate. This is reasonably true because long segments provide more space for drivers to execute maneuver such as lane changes for overtake because there is sufficient gaps available between vehicles. Note that segment length is not a significant variable for EN-EX segments on I-15, an observation counter expectation. This needs further investigation.

EN-EX segments on US95: There were only two variables that are statistically significant: radius of curve and shoulder width. Their signs are the same as those on the other two freeways.

The results for the EX-EN segments in Table 5.5 are quite similar to those of the EN-EX segments, with the following exceptions. First, the number of through lane has different signs in the models for I-15 and I-215, but their signs are opposite in the case for EN-EX. This will be further investigated. Second, traffic flow AADT becomes significant, which is not significant in the models for EN-EX segments. This might reflect the situation where traffic congestion back into from EN-EX segment to EX-EN segments, as the increase of traffic flow. The impact of traffic may not be observed on the EN-EX segments, but on the EX-EN segments. Third, segment length is not a significant variable for EX-EN segment which is the case for the EN-EX segments. In other words, segment length is important to EN-EX segments than EX-EN segments. One reason might be that traffic weaving that causes crashes on EN-EX may not be a significant problem on the EX-EN segments. These three observations make EN-EX segments different from EX-EN segments.

5.3 Severity model

Table 5.6 presents results estimated from severity model. The likelihood ratio tests for all models indicate that they are statistically significant. For EN-EX segments on I-15, only the number of through lanes, shoulder, and median width was statistically significant.

Table 5.6: Ordered Probit Model Results

EN-EX segment									
Variable	**I-15**			**I-215**			**US95**		
	Coef.	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**
Through lanes	0.628	0.180	3.490	15.735	5.748	2.740	-0.278	0.108	-2.570
Shoulder width	-0.709	0.267	-2.660	-7.599	2.763	-2.750	-0.365	0.080	-4.590
Median width	-0.480	0.142	-3.370	-0.850	0.430	-1.980			
_Cut1	11.910	4.219		39.736	17.001		4.529	1.001	
Auxiliary statistics									
LR chi2(15)	68.39			62.34			30.4		
Prob > chi2	0.000			0.0000			0.0000		
Pseudo R2	0.4120			0.8491			0.1954		
Number of Crashes	131			78			115		
EX-EN segments									
Variable	**I-15**			**I-215**			**US95**		
	Coef.	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**	**Coef.**	**Std. Err.**	**Stat.**
Through lanes	2.201	0.825	2.670	1.687	0.391	4.310	-0.505	0.128	-3.940
Shoulder width	-3.012	0.807	-3.730	-0.332	0.084	-3.940	-0.138	0.036	-3.800
Median width				-0.151	0.041	-3.660			
Cut_	18.785	9.128		-0.022	1.633	-0.010	2.365	0.660	
Auxiliary lanes									
LR chi2(15)	48.35			120.92			24.66		
Prob > chi2	0.0000			0.0000			0.0000		
Pseudo R2	0.4526			0.5120			0.1330		
Number of rashes	109			187			162		

EN-EX segments on I-15: only the number of through lanes, shoulder, and median width was statistically significant. The coefficient on the number of through lanes on I-15 is positive which indicates that more lanes on EN-EX segment on I-15 increased the likelihood of more severe crash (e.g., injury crashes or fatality). This can be explained by the fact that more lanes attract more vehicles to use the facility and this increases the likelihood of crash occurrence. Observed dataset indicated that sideswipe collision increased with the number of through lanes. In this case it should be noted that sideswipe collisions occur when two vehicles are traveling side-by-side in the same direction and one vehicle drifts into the lane next to it, swiping the other vehicle. This indicates the existence of more lane changes related to segments with more lanes.

The coefficient on the shoulder width is negative which implies that wide shoulders reduce the likelihood of high severity crashes. It might be due to the fact that more space is available for emergency storage of disabled vehicles and maintenance activities. Storage of disabled vehicles reduces the risk of rear-end crashes and prevent a lane from being closed. Shoulders also provide a space for drivers to maneuver to avoid crashes, improve stopping sight distance at curves, as well as recovery area for drivers who have left the travel lane. The coefficient on the median width is negative which indicates that wide medians reduced the likelihood of high severity crashes. This is because medians may be used as recovery areas by out-of-control vehicles in the case where a median is unprotected.

EN-EX segments on I-215: the results are similar to those on I-15.

EN-EX segment on US 95: the coefficient on the number of through lanes is positive which indicates that more lanes increased the likelihood of high severity crashes. This observation is the opposite of that for other two freeways, and need further investigation. The coefficient on the shoulder width is negative, the same for other two freeways. However, the coefficient for median width is not significant, different from other two freeways. These two differences reflect the distinct characteristics of US 95 comparing other two freeways.

The results for EX-EN segments on these three freeways are similar to those on EN-EX segments, with the exceptions on median width for EX-EN segment on I-15. For the EN-EX segment, wider median reduce the likelihood of high severity crash. In the case of EX-EN, lane changing activities are reduced comparing on EN-EX, and thus the function for median to provide buffer to out-of-track vehicles is diminished, and thus the variable become not significant. It can also be seen from Table 5.6 that the relative magnitude of the influence of the variables are different from those on the EN-EX segments.

CHAPTER 6 - IDENTIFYING THE SEGMENTS WITH GEOMETRIC DESIGN PROBLEMS

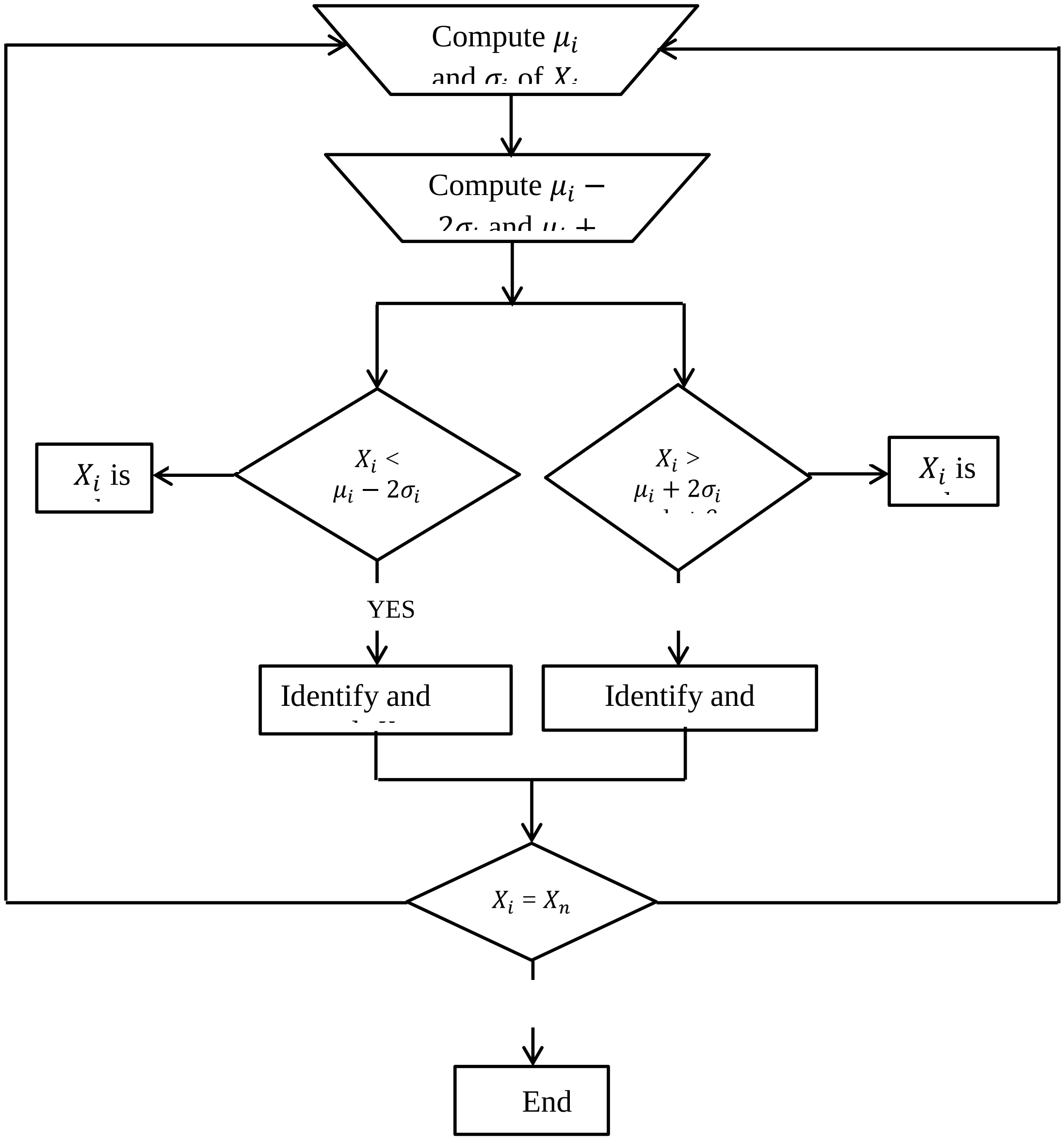
This study used the results from regression models to identify the segments with geometric design problems. Segments with geometric characteristics values above or below their corresponding mean by two standard deviations imply that they present potentials for crashes due to geometric design problems. Figure 6.1 presents the steps to sort out these segments. The notations used on the flow chart are provided below:

X_i : a significant variable from the regression results and $i = 1, \ldots, n$,

μ_i : computed mean of a variable X_i,

σ_i : computed standard deviation of a variable, X_i, and

β_i: regression coefficient for a variable X_i.


Compute μ_i
and σ_i of X_i
Compute $\mu_i -$
$2\sigma_i$ and $\mu_i +$
X_i is
$X_i <$
$\mu_i - 2\sigma_i$
$X_i >$
$\mu_i + 2\sigma_i$
X_i is
YES
Identify and
Identify and
$X_i = X_n$
End

Presented in Tables 6.1 and 6.2 are the segments on each of the three freeways based on crash rate and severity models, respectively. The results are also presented in Tables 6.3 and 6.4 list the segments with their geometric problems.

Table 6.1: Influencing factors for crash rate model

EN-EX segments

Variable	I-15			I-215			US 95		
	Coef. sign	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$
Through lanes	+			-					
Radius of curve	-		35	-		10 & 34	-		
Shoulder width	-			-		34 & 75	-		83, 86 & 102
Median width	-		18	-		13 & 34			
Segment length				-		2 & 51			

EX-EN segments

Variable	I-15			I-215			US 95		
	Coef. Sign	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$
Through lanes	+			-	3	23, 52 & 84			
Radius of curve	-		20	-			-		90
Shoulder width	-			-		4, 23 & 68	-		90 & 99
Median width	-			-		16, 23, 35 & 92			
Segment length				-					
AADT				-		64, 89 & 95			

Table 6.2: Influencing factors for severity model

EN-EX segments									
Variable	**I-15**			**I-215**			**US 95**		
	Coef. Sign	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu-2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$
Through lanes	+		33, 35 & 61	-					
Shoulder width	-	50 & 61		-			-	37	98
Median width	-	40, 43 & 64		-		13 & 34			

EX-EN segments									
Variable	**I-15**			**I-215**			**US 95**		
	Coef. Sign	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$	**Coef. Sign**	$\mu+2\sigma$	$\mu-2\sigma$
Through lanes	+		36 & 72	-	3, 7, 56 & 92		-	115	
Shoulder width	-		9, 42 & 55	-	104		-	39 & 113	
Median width	-			-		16, 35, & 92			

Table 6.3: Influencing factors for EN-EX segments

EN-EX on I-15					
segno	**crash freq**	**crash rate**	**Crash rate factor**	**Severity factor**	**Remarks**
18	54	1.4149	Median		Highest crash rate = 1.4149
35	2	0.3189	Radius	Lanes	
EN-EX on I-215					
segno	**Crash freq**	**Crash rate**	**Crash rate factor**	**Severity factor**	**Remarks**
34	13	3.3011	Shoulder, Median, & Radius	Median	Highest crash rate = 3.3011; Factor values are two std Dev. below mean values
51	1	0.1522	Length		
2	1	0.1030	Length		
13	3	0.0521	Median	Median	
10	0	0	Radius		
75	0	0	Shoulder		
EN-EX on US95					
segno	**crash_freq**	**crash rate**	**Crash rate factor**	**Severity factor**	**Remarks**
86	18	1.1789	Shoulder		Highest crash rate=1.1789; Factor values are two std Dev. Below mean values
102	6	0.3665	Shoulder		
83	0	0	Shoulder		
98	4	0.2774		Shoulder	

Table 6.4: Influencing factors for EX-EN segments

EX-EN on I-215					
segno	**crash_freq**	**Crash rate**	**Crash rate factor**	**Severity factor**	**Remarks**
23	17	1.3638	Lanes, Shoulder, Median		Highest crash rate = 1.3638; Factor values are two std Dev. Below mean values
16	8	1.2573	Median	Median	
52	22	0.7653	Lanes		
68	26	0.6757	Shoulder		
84	4	0.6174	Lanes		
4	8	0.2052	Shoulder		
35	3	0.1448	Median	Median	
64	2	0.0683	AADT		
95	0	0	AADT		
89	0	0	AADT		
92	0	0		Median	
EX-EN on US95					
segno	**crash_freq**	**Crash rate**	**Crash rate factor**	**Severity factor**	**Remarks**
90	36	1.3162	Shoulder		Highest crash rate = 1.3162
99	11	0.4134	Shoulder		

To verify the geometric problems on these segments, local highway design experts were consulted. Meetings with them were made where the results listed in Tables 6.3 and 6.4 were presented to them segment-by-segment. If the identified geometric problems are not consistent with their perceptions, they provided the possible geometric problems they perceived. For each segment, discussions on countermeasures to improve safety were also made. The sections below list the discussions and the countermeasures.

SEGMENTS ON I15

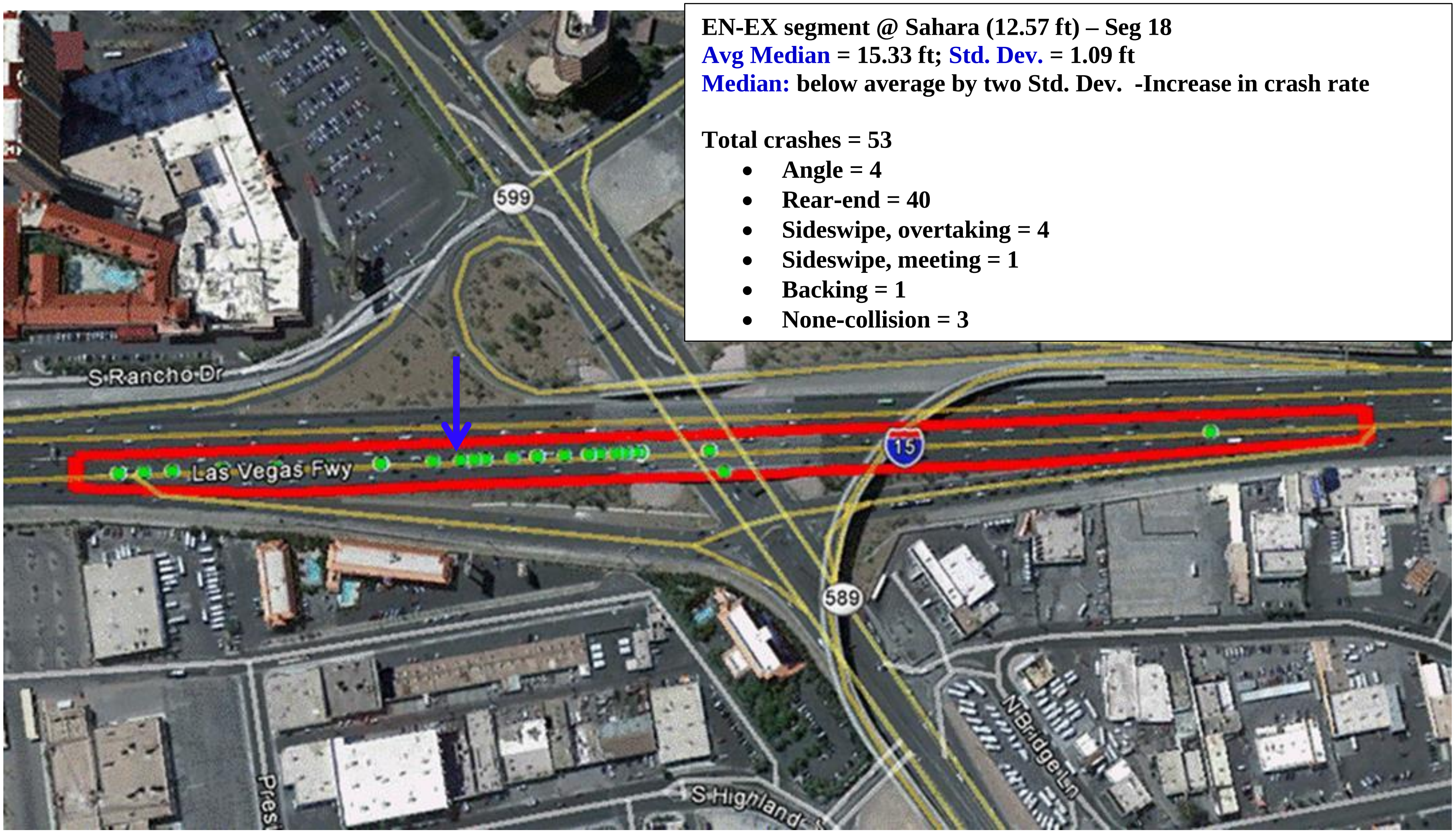


Figure 6.2 Segment 18

Segment #18 is located on Northbound I15 at Sahara Av. The on-ramp has three lanes and the merging traffic causes significant traffic congestion which would move upstream, initially with right most lane blocked, ultimately with all mainline lanes blocked, during peak period. The model indicates that this segment experienced an increase in crash rate due to narrow median. Observation on non-geometric factors indicated that many crashes occurred when pavement surface was wet and when traffic was in peak period. Many of these crashes are rear-end. It is likely that the cause of the crash are temporary reduction of pavement surface friction, but not narrow median that are revealed through the methodology used in this study.

Meeting with experienced professionals revealed that congestion is the primary contributing factor for crash occurrence. When congestion starts in peak period, drivers on the mainline tend to drive on the right side lane and merge at the end, while queues develop at the merge of main facility and entry ramp. Significant amount of weaving movement downstream of this segment causes congestion. It was indicated that the effective way of removing the weaving is separating the involved traffic movement spatially. Neon project has included some improvements regarding this.

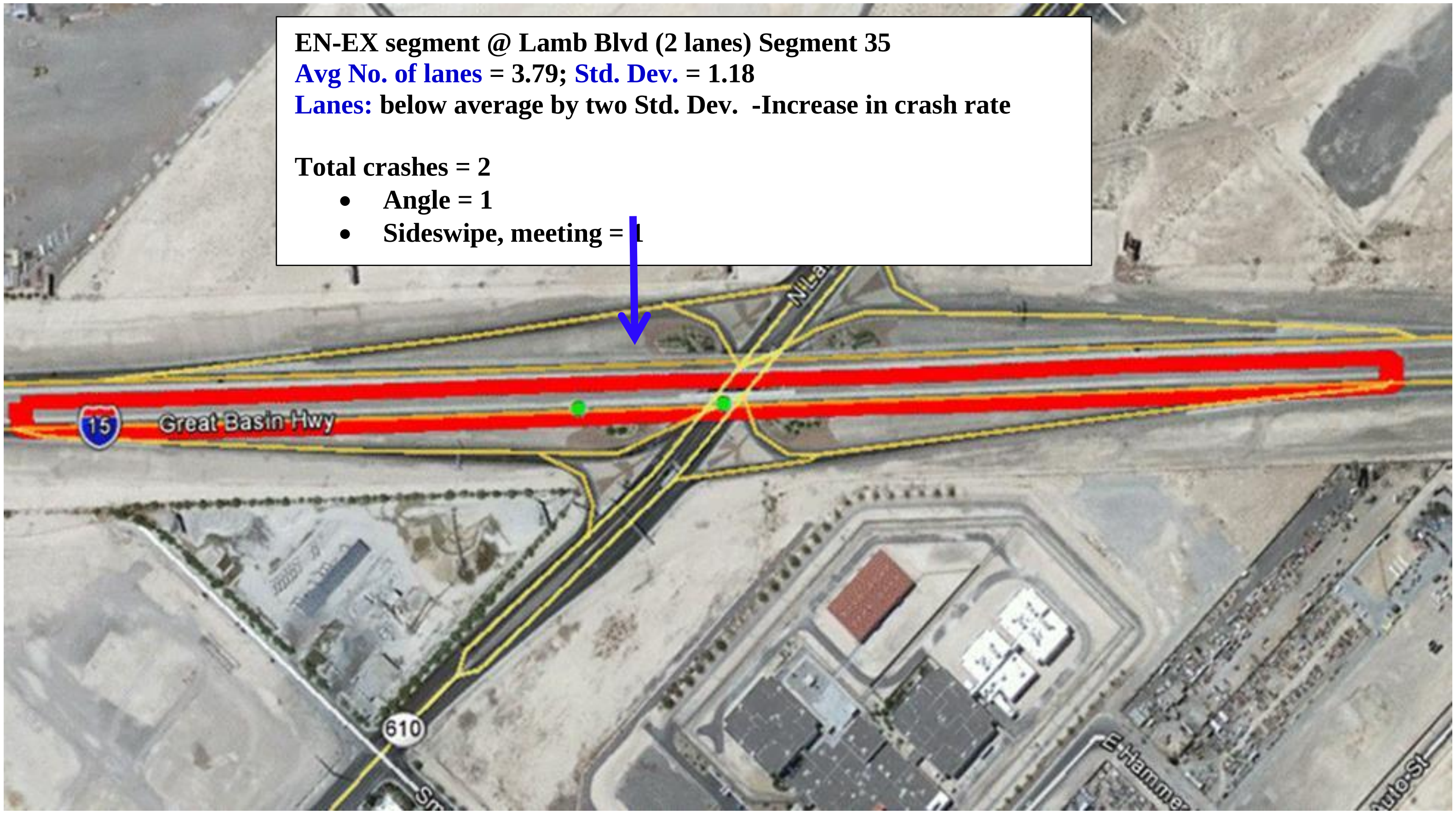
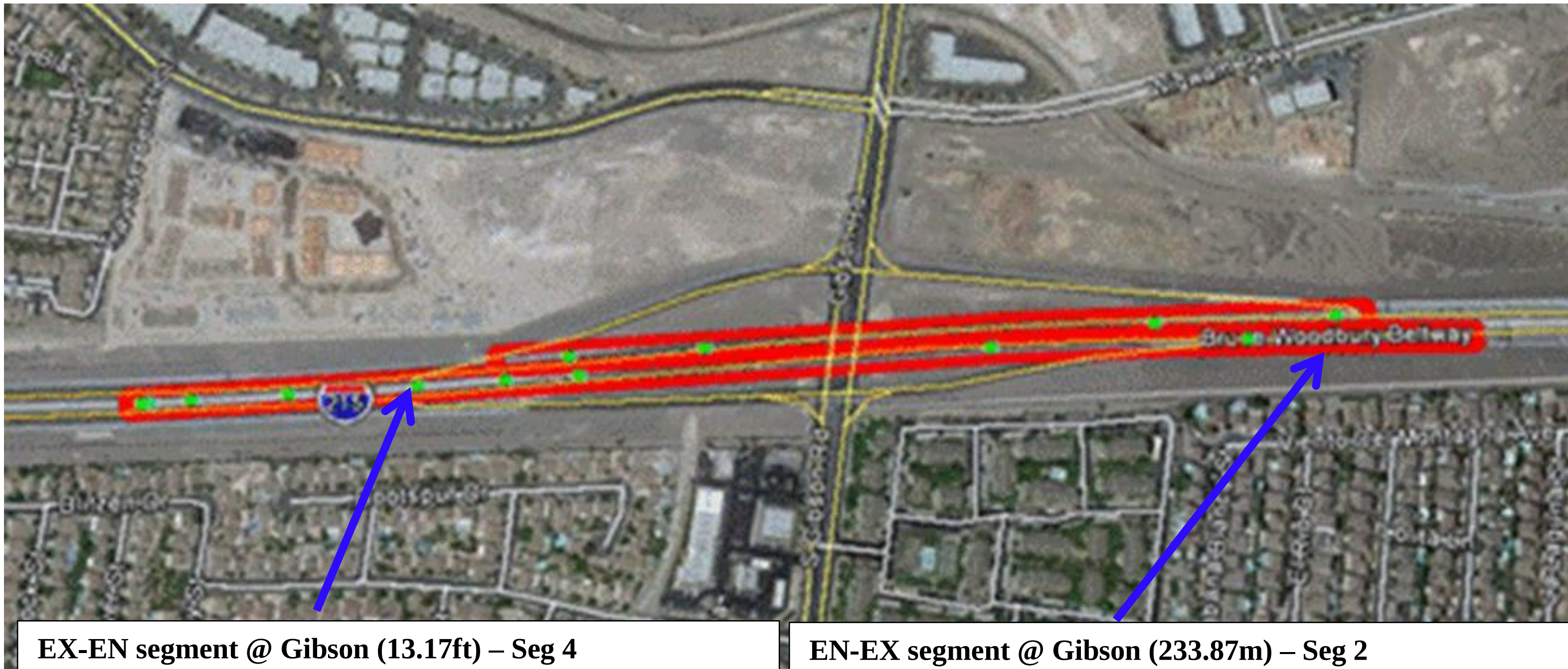


Figure 6.3 Segment 35

Segment 35, northbound I-15 at Lamb Blvd, shown in Figure 6.3 has only two crashes happened, one of which occurred on wet pavement surface. Both crashes occurred on dark condition. Although the lighting may be the probable cause, it may not be conclusive due to few crashes observed.

Consultation with other professionals indicated that driver behavior may likely have contributed to crash occurrence. It was suggested that traffic volume should further be investigated and an additional lane might be added if needed.

SEGMENTS ON I-215



EX-EN segment @ Gibson (13.17ft) – Seg 4
Avg Shoulder = 11.33 ft; Std. Dev. = 2.00 ft
Shoulder: below average by two Std. Dev. -Increase in crash rate

Total crashes = 9

- **Angle = 1**
- **Rear-end = 3**
- **Sideswipe, overtaking = 1**
- **None-collision = 4**

EN-EX segment @ Gibson (233.87m) – Seg 2
Avg length = 802.47m; Std. Dev. = 407. 84m
Length: below average by two Std. Dev – Increase in crash rate

Total crash = 1

- **Rear-end type**

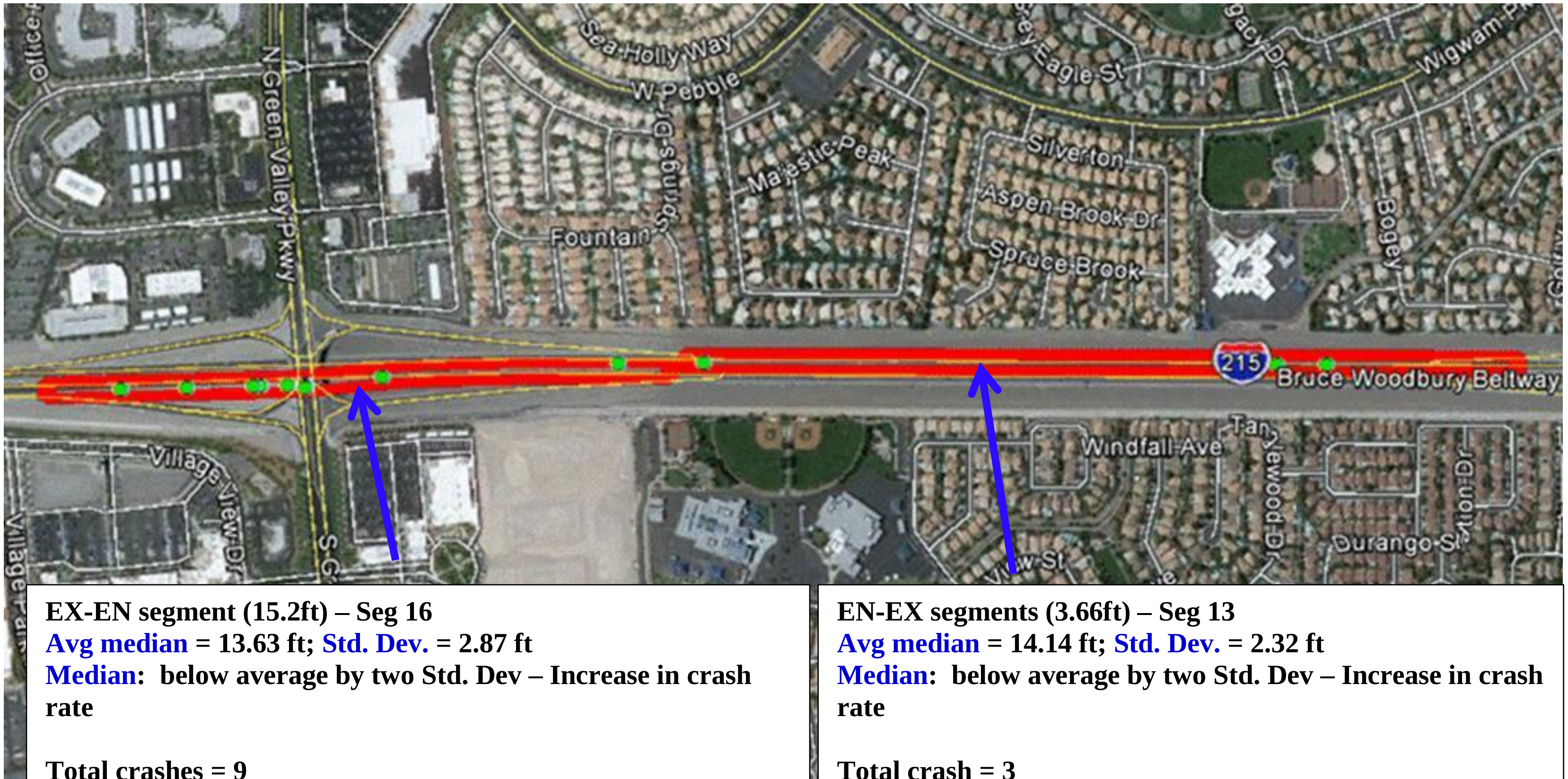
Figure 6.4 Segments 2 and 4

Segment 2

Segment 2 is at Gibson on Eastbound I-215, starting at the on-ramp to I-215. There was only one rear-end crash happened on this segment. The modeling results in Table 3 indicated that short length of the segment may contribute to the occurrence of crashes on this segment. Further looks at the crash data, it is revealed that the crash occurred during peak hour period and on wet pavement surface. Thus, the short segment length may not the sole contributing factor of the crash. The professionals consulted who worked on these freeways indicated that congestion problems and the time the segment experienced congestions may likely have contributed to crash occurrence. Ramp metering could be effective at this location in reducing the conflict of traffic on mainline near the ramp.

Segment 4

Segment 4 is at Gibson Rd on I-215 Eastbound, covering the entire interchange bridge. The modeling used in this study indicates that Segment 4 had a narrow shoulder which would potentially contribute to an increase in crash rate. The crash data indicated that significant number of rear-end crashes occurred during the peak period. Other crashes occurred on wet pavement surface. There are significant number of non-collision occurred. These crash types and related conditions when crashes occurred suggests that narrow shoulder may not be the factor significantly contributing the occurrence of these crashes. The professionals we consulted indicated that congestion on the off-ramp would spill back onto freeway, causing rear-end crashes. When vehicles on freeway run at high speed, they may lost control and end up with different type of incidents. It was suggested to adjust the signal timing at Gibson Rd., making sure that the green light can be provided to the off ramp traffic sufficiently so that the congestion on the ramp can be controlled at local level.



EX-EN segment (15.2ft) – Seg 16
Avg median = 13.63 ft; Std. Dev. = 2.87 ft
Median: below average by two Std. Dev – Increase in crash rate

Total crashes = 9

- **Angle = 2**
- **Rear-end = 5**
- **Sideswipe, overtaking = 2**
- **None-collision = 3**

EN-EX segments (3.66ft) – Seg 13
Avg median = 14.14 ft; Std. Dev. = 2.32 ft
Median: below average by two Std. Dev – Increase in crash rate

Total crash = 3

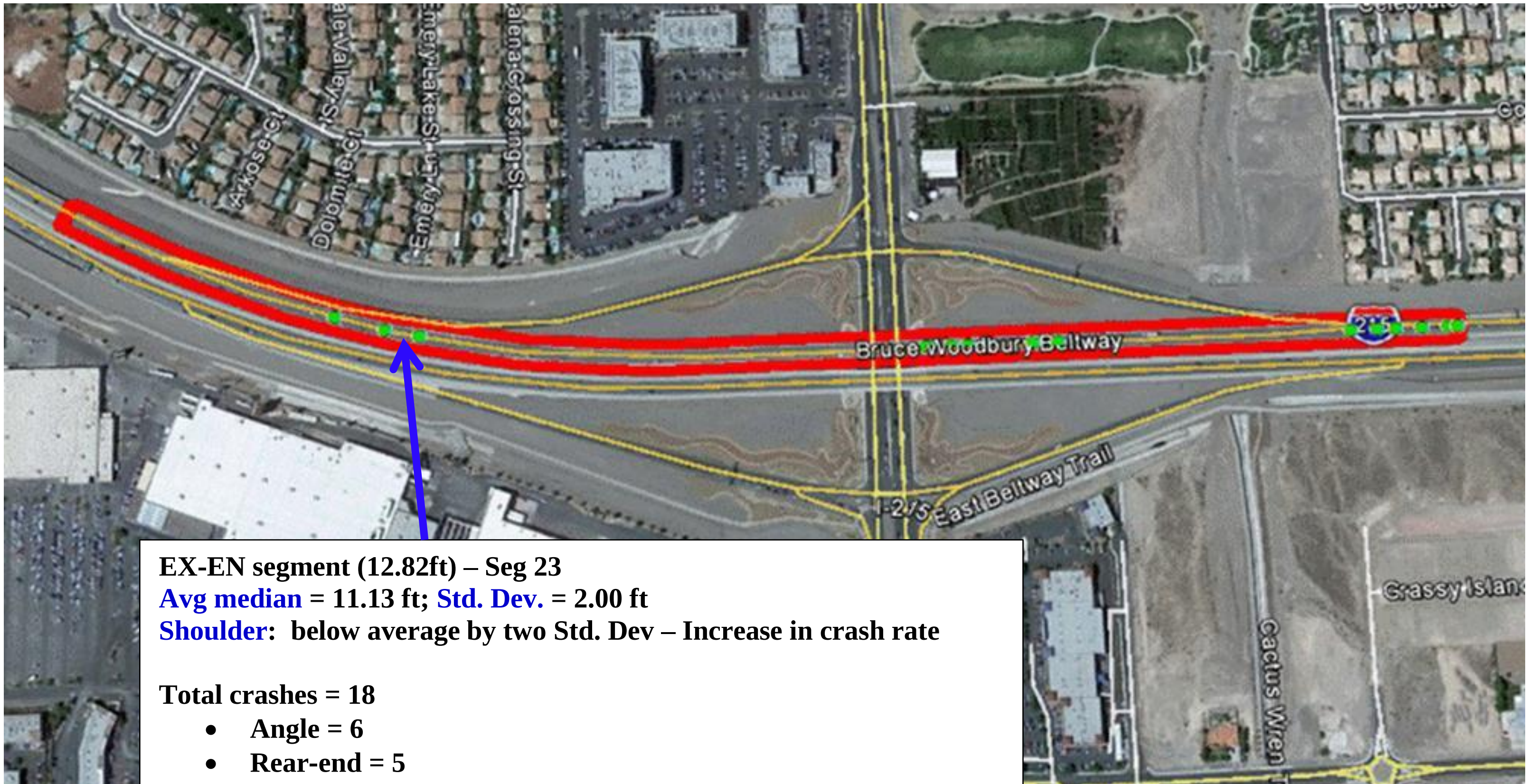
- **Angle = 2**
- **Non-collision = 1**

Figure 6.5 Segments 13 and 16

Segment 13

Segment 13 is on westbound I-215 between Valle Verde Dr. and Green Valley Pkwy. The modeling indicated that narrow median is a contributing factor for crashes at this segment. The crash data show that two crashes were angle crash which occurred during peak hour period. This segment is long upgrade, and there was a full auxiliary lane connecting these two interchanges. Thus, it is hard to figure out the cause of the crashes.

Segment 16 is at Green Valley Pkwy on eastbound I-215, running from one side of the interchange to the other side. The modeling indicates that narrow median might be a contributing factor for the occurrence of crashes. The crash data present that significant rear-end crashes happened on this segment. These crashes were highly likely caused by traffic from the eastbound on-ramp. The District in that area and the Green Valley Ranch Casino may generate traffic that makes the traffic significantly congested the on-map to Henderson. In addition, St. Rose Pkwy carries significant traffic that feeds to this segment. Thus, it was suggested to have ramp metering on this ramp on Green Valley Pkwy and St. Rose.



EX-EN segment (12.82ft) – Seg 23
Avg median = 11.13 ft; Std. Dev. = 2.00 ft
Shoulder: below average by two Std. Dev – Increase in crash rate

Total crashes = 18

- **Angle = 6**
- **Rear-end = 5**
- **Sideswipe, overtaking = 1**
- **None-collision = 9**

Figure 6.6 Segment 23

Segment 23

Segment 23 is on a big curve at Eastern Ave. on the westbound of I-215. Crashes distributed. It was identified by the models that the numbers of lanes and widths of shoulder and median are below average, and thus could be the contributing factors to the occurrence of crashes on this segment. It is further observed that the segment has three different locations where crashes occurred. At the exit terminal, the observed data indicated that there are more rear-end crashes which occurred during peak hour period on wet pavement surface. The traffic volume on-ramp from Eastern Ave. is usually very high because it is a major arterial in this area of the freeway. The weaving of traffic at this location is very heavy. Ramp metering should be considered at this location. In addition, the on-ramp is a tapered type, which should be changed to parallel type, making the entrance of traffic to mainline easier. It is noticed that the space around the on-ramp is sufficiently large to make such a change.

At the middle of the segment, there were also crashes happened. These crashes are comprised of angle, rear-end, and sideswipe in approximately equal proportion. A great number of crashes occurred during peak period on wet pavement surface. These crashes may be caused by the congestion at the exit terminal downstream. A warning sign with dynamic message is suggested to alert the motorist running at high speed.

There are few numbers of crashes observed at the entrance which occurred on wet pavement surface with only crash happened during peak period. It is noticed that the traffic to the off-ramp is very heavy during peak period, and these traffic may backup to freeway mainline, causing traffic turbulence, which would influence driver behavior passing the off-ramp. A warning sign of slow-moving vehicles downstream is more appropriate to be installed for this location.

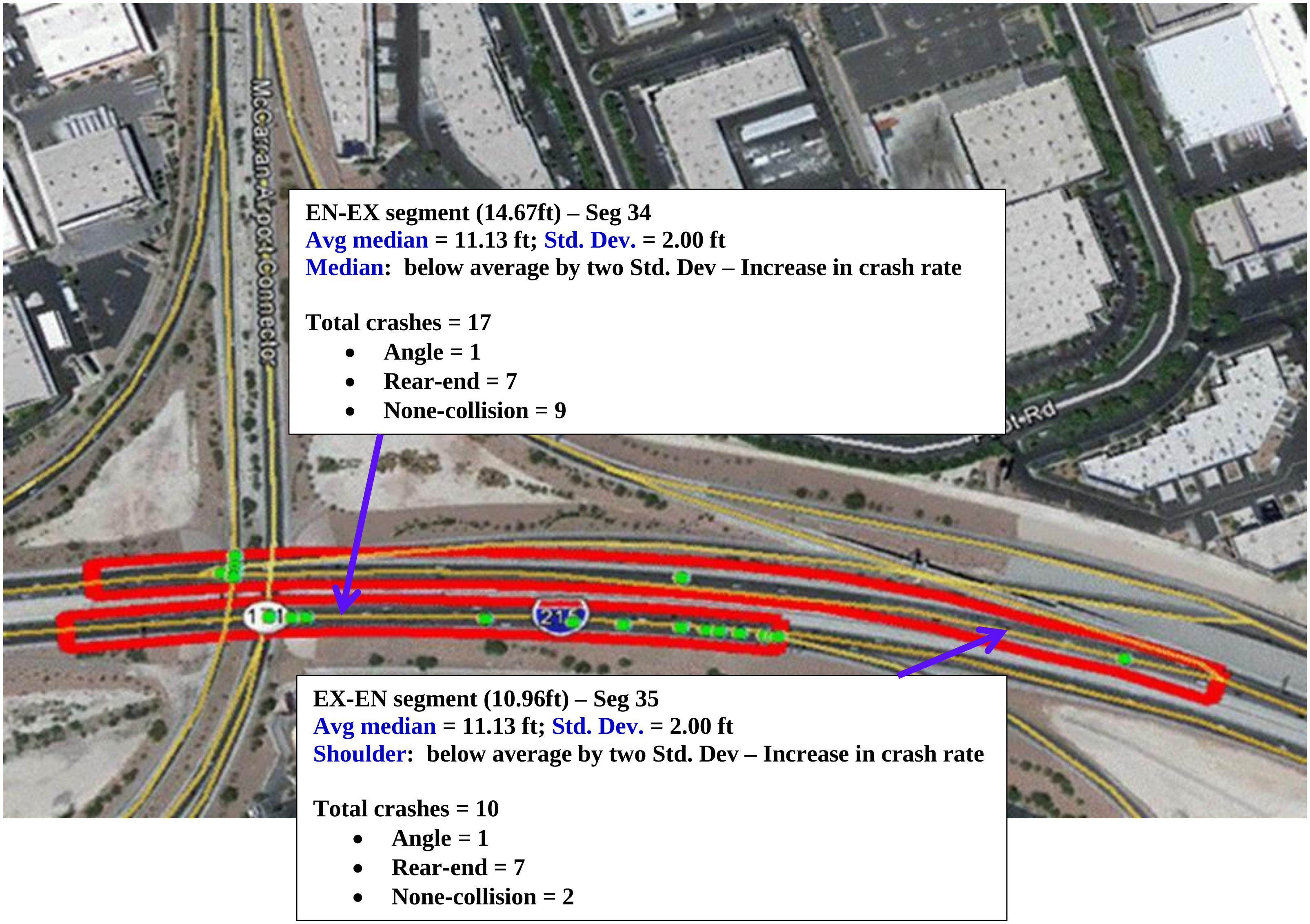


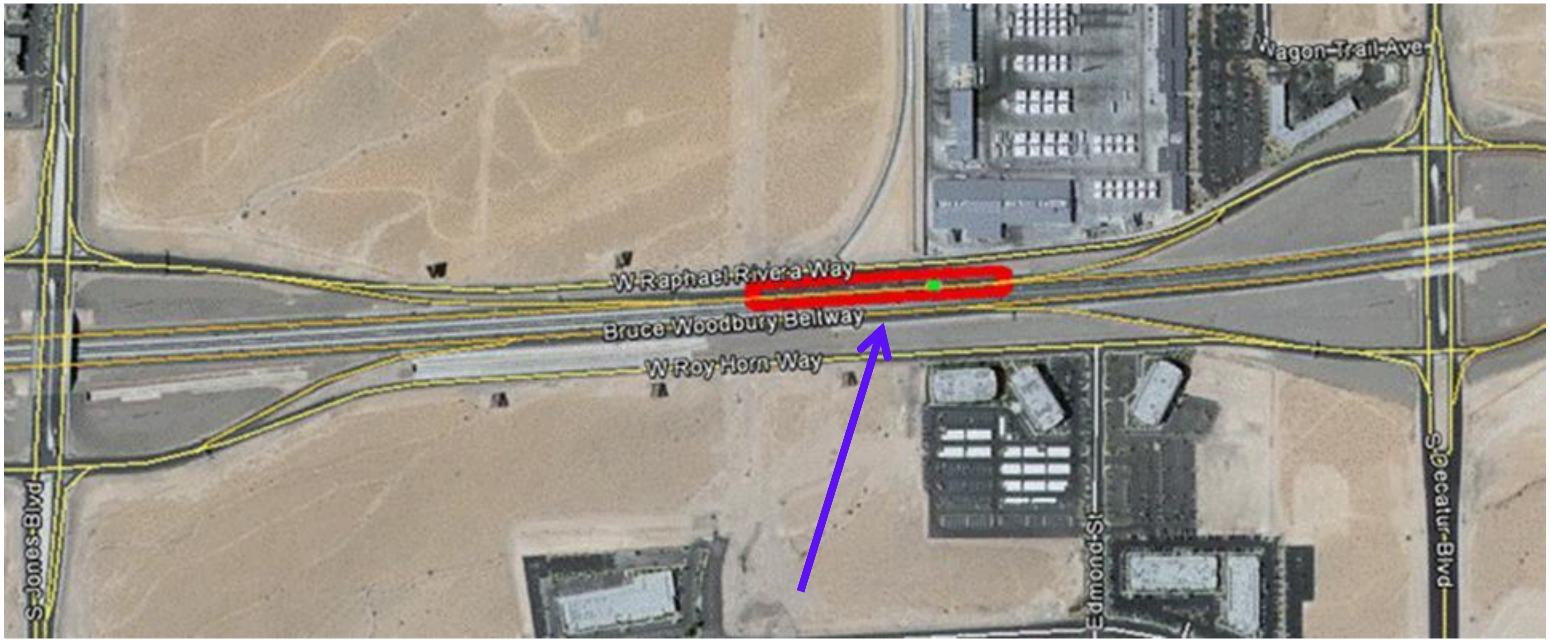
Figure 6.7 Segments 34 and 35

Segment 34

Segment 34 is at the airport connector on the Eastbound I-215. The modeling results indicated that the widths of shoulder and median are narrow, and radius of curve is sharp on segment 34, which would have contributed to the occurrence and severity of crashes. Crash data indicated that there were more rear-end crashes occurred at the exit terminal. In general, these crashes occurred when the pavement was wet and during the peak hour period with a Dark-sport lighting condition. As a matter of fact, this segment involved significant traffic weaving: the traffic from the airport and the west of I-215 conflicting with traffic getting off I-215 on the off-ramp. Particularly when the traffic on the off-ramp cannot be cleared quickly, this situation becomes the worst. From the meeting with some experts in road design it was known that this segment will be widened so that more lanes can be dedicated to weaving. A flyer from the airport to Eastbound I-215 will be constructed, which separate the weaving traffic spatially. This construction is expensive, but will solve the congestion and safety problem significantly.

Segment 35

Segment 35 is at the airport connector of westbound of I-215. The modeling results indicate that the narrow median at this segment would contribute to the crash occurrence significantly. Actually, the influencing factors would be more coming from traffic in the connected road segments. At the downstream end, it was a merging point for traffic from the airport going to the west. Congestion has always been formed at this point and the segment downstream, which conflicts with the through traffic on this segment. This might be a reason for having many crashes at this point. This problem would be reduced by building an elevated structure that can allow the traffic from the airport to go to the west of Las Vegas Blvd. The database indicates that the pavement surface was wet at the time of crash occurrence and these crashes are associated with a greater number of rear-end crashes at this spot. The database also indicates that more young drivers were involved compared to old drivers. At the middle of this segment, two crashes were observed which involved old drivers on wet pavement surface. This implies that age combined with pavement condition factors may likely have contributed to crashes. At the upstream end of this segment, traffic turbulences were usually formed due to the congestion on the off-ramp to the airport. Travelers may behave differently after they move out the turbulences, causing more crashes. This problem would be mitigated by building a flyer from eastbound I-215 to the airport, separating the traffic from both directions of I-215 merging and weaving at the point right before the tunnel.



EN-EX segment (273.26m) – Seg 51
Avg length = 802.47 m; Std. Dev. = 407.84 m
Length: below average by two Std. Dev – Increase in crash rate

Total crashes = 1 (None-collision)

Figure 6.8 Segment 51

Segment 51

Segment 51 is the segment on westbound I-215 between Decatur Blvd and Jones Blvd. This segment is very short, and the modeling results show that the segment length would be a contributing factor to the crashes on this segment. The dataset registered only one crash involved a driver aged 65 years occurred during rainy season and normal daylight. Since there was only one crash recorded, it cannot indicate clearly whether it was caused by geometric characteristics or non-geometric characteristics.

According to the experts consulted in this project, driver behavior like speeding also may likely contribute to crash occurrence, for which further investigation based on real-time data may be able to capture unobserved underlying reasons contributing to crash occurrence.

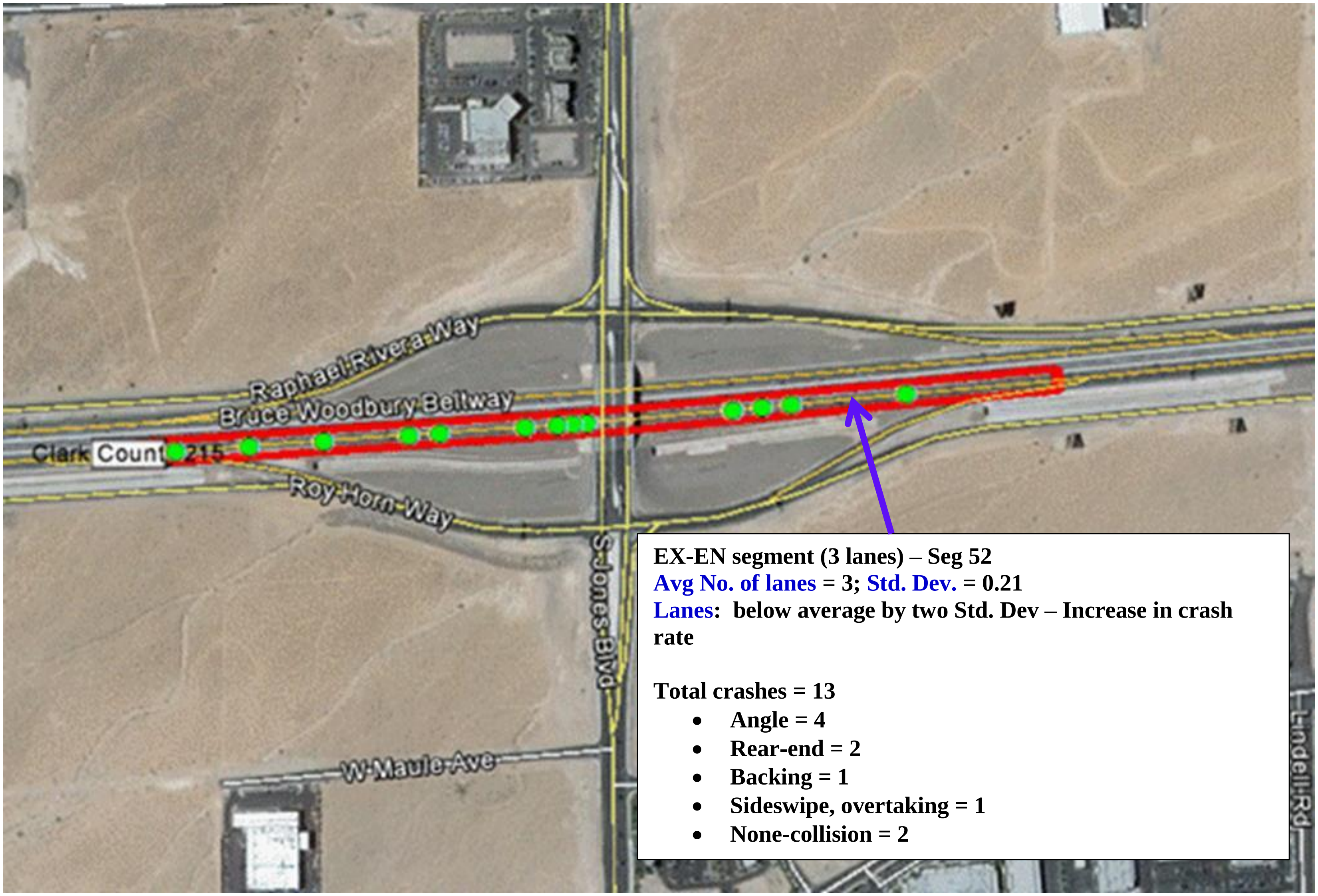


Figure 7.9 Segment 52

Segment 52

Segment 52 is at Jones Blvd on the eastbound of I-215. There was fewer number of lanes than average. The modeling results imply that this would have contributed to the crash occurrence at this location. At the upstream location of this segment, an angle crash happened during darkness and on wet pavement surface with a driver action as changing lanes. At the downstream location, another angle crash occurred on wet pavement surface. These crash data imply that it would be non-geometric factors that contributed to a greater extent to the occurrence of crashes, for which other data are needed to identify the causes of the crashes.

The design experts suggested that speeding and the time when a crash happened may have likely contributed to crash occurrence. Additional signage may help alleviate speeding by informing drivers as they approach the segment.

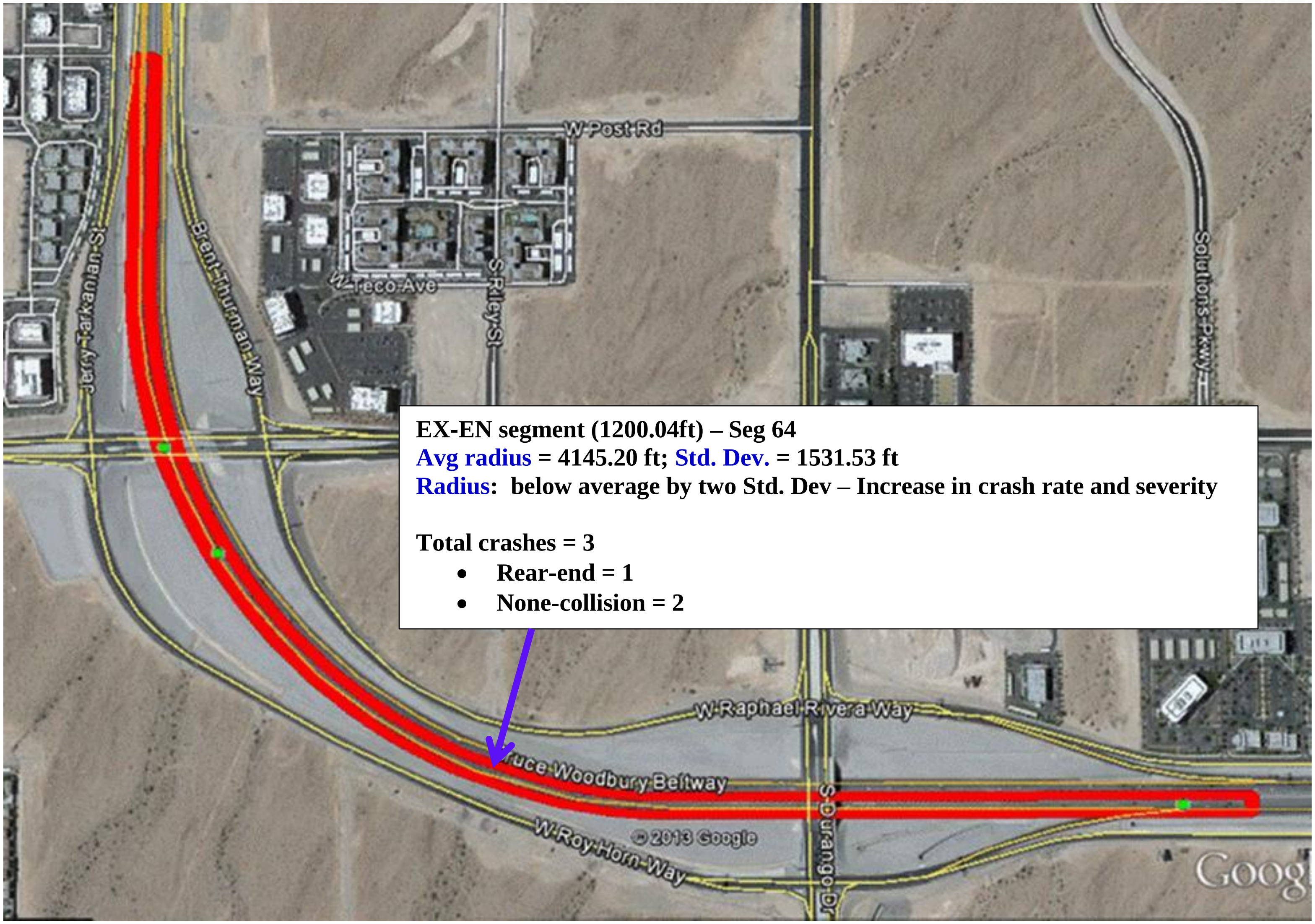


Figure 6.10 Segment 64

Segment 64

Segment 64 is at Durango Dr. on eastbound I-215. It is a long curve. The modeling results indicate that high traffic volume would contribute the occurrence of crashes on this segment. An increase in traffic may likely induce more crashes, which probably would be rear-end. However, only three crashes were observed from the database with only one crash being a rear- end crash. Thus, the crash type was not correspondent to the traffic flow.

The highway design experts consulted in this study indicated that vehicles tended to drive at speed beyond the design speed, which may have contributed to crashes. It was suggested that putting signs to alert drivers of speeding may likely reduce crashes.

EX-EN segment @ Russell Rd (3 lanes) – Seg 68
Avg No. of lanes = 3; Std. Dev. = 0.21
Lanes: below average by two Std. Dev – Increase in crash rate

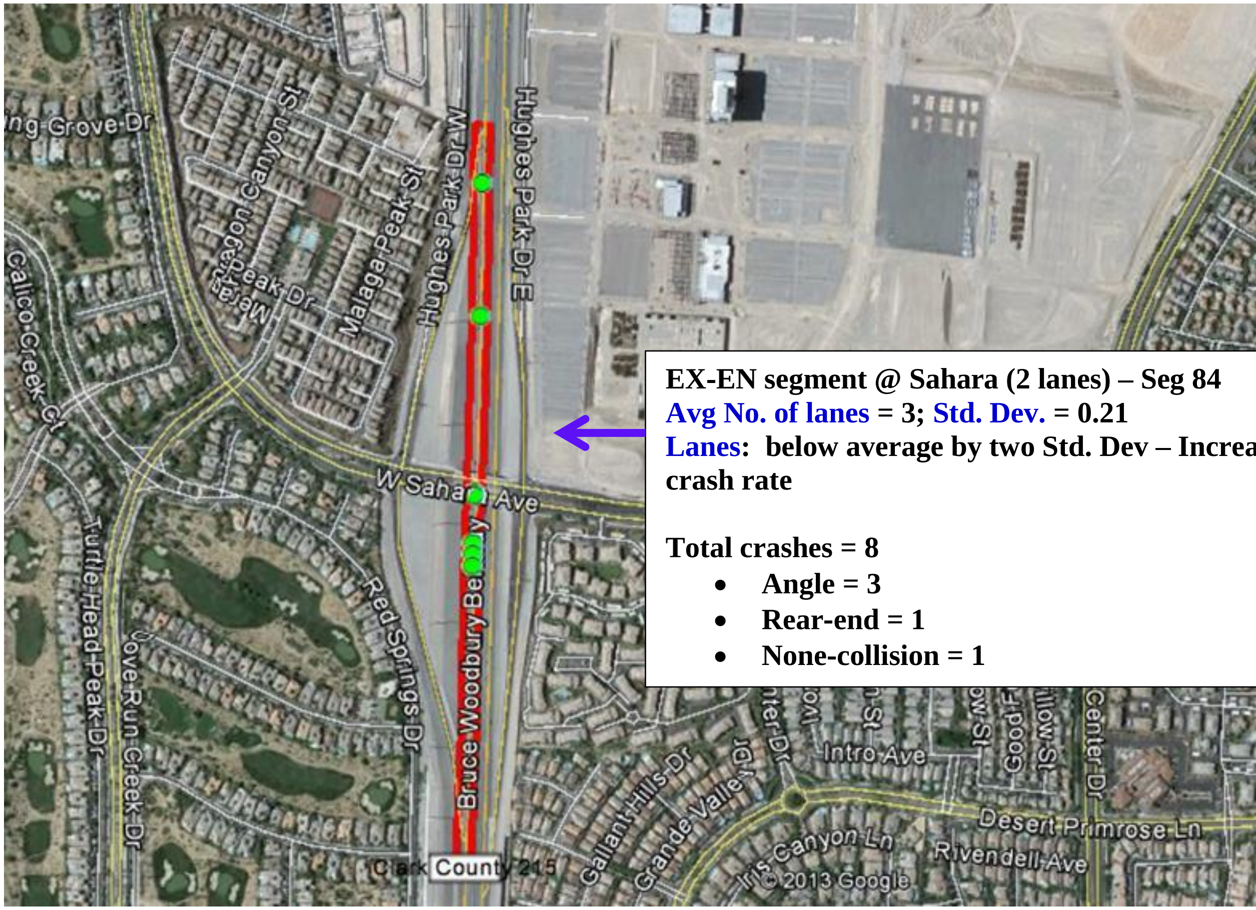
Total crashes = 18

- **Angle = 1**
- **Rear-end = 10**
- **None-collision = 7**

Figure 6.11 Segment 68

Segment 68

Segment 68 is at Russell Rd. on eastbound of I-215. It had a narrow shoulder, which was identified to have had contributed to the occurrence of crashes. The crash data indicate that there were ten rear-end crashes out of 18 crashes happened on this segment. In addition, these crashes happened on wet pavement surface during peak hour period and dark condition, which might have actually influenced the occurrence of crashes than shoulder. It is also observed that there were seven crashes that were non-collision, which was very hard to figure out the cause of crashes without real-time data.



EX-EN segment @ Sahara (2 lanes) – Seg 84
Avg No. of lanes = 3; Std. Dev. = 0.21
Lanes: below average by two Std. Dev – Increase in crash rate

Total crashes = 8

- **Angle = 3**
- **Rear-end = 1**
- **None-collision = 1**

Figure 6.12 Segment 84

Segment 84

Segment 84 is located at Sahara Ave. on eastbound I-215. The modeling results indicate that there was fewer number of lanes on this segment which would have contributed to the crash occurrence on this segment. However, the crash data shows that most crashes happened during peak hour period which suggests congestion may be more lightly contributing to these crashes. Without real time data it is difficult to understand the underlying problems for these crashes.

SEGMENTS ON US95

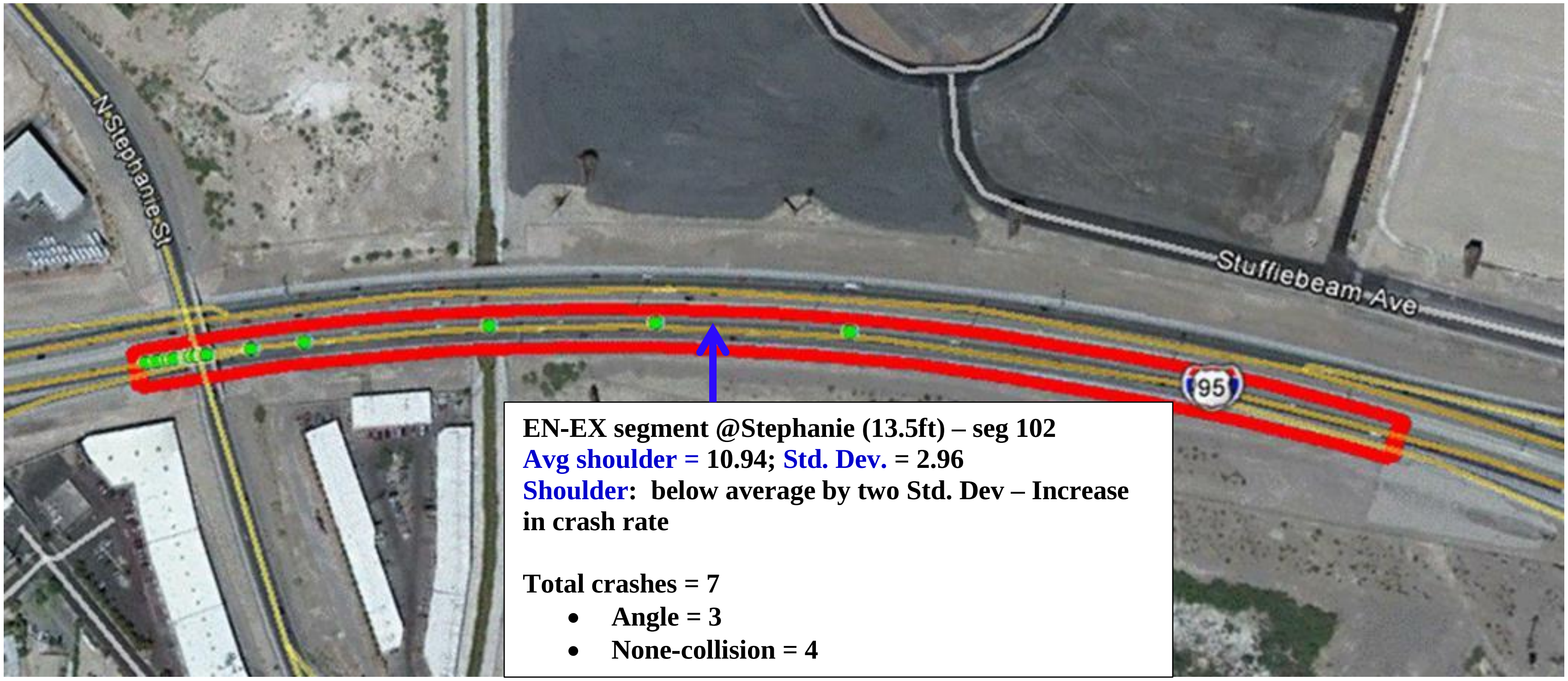


Figure 6.13 Segment 102

Segment 102

Segment 102 is at Russell Rd. on the southbound of US 95. It is an EN-EX segment between the Russell and Galleria Dr. interchanges. Its shoulder was narrow which was identified to cause more crashes. There were three crashes in total happened on this segment, and these crashes were associated with wet pavement surface. The design experts consulted indicated that vehicles tended to speeding on this downgraded segment, which may likely contribute to the occurrence of these crashes. It was suggested that putting signs to alert speeding to reduce crash occurrence. In addition, due to relatively few crashes observed in this segment, more real-time data are needed to identify the underlying causes of crashes.

EN-EX segment @ Harmon Ave (10.9ft) – Seg 98
Avg shoulder = 11.20; Std. Dev. = 3.32
Shoulder: below average by two Std. Dev – Increase in crash rate

Total crashes = 4
- **Rear-end = 2**
- **None-collision = 2**

EX-EN segment @ Tropicana (11.9ft) – seg 99
Avg shoulder = 11.20; Std. Dev. = 3.32
Shoulder: below average by two Std. Dev – Increase in crash rate

Total crashes = 11
- **Rear-end = 3**
- **Sideswipe, meeting = 1**
- **Sideswipe, overtaking = 1**
- **None-collision = 6**

Figure 6.14 Segments 98 and 99

Segment 98

Segment 98 is at upstream before the Tropicana Interchange on the southbound of US 95. The shoulder on the segment is narrow, which, according to the modeling results, would have contributed to the crash occurrence. There were only four crashes observed which occurred during non-peak period on wet pavement surface, which might make it hard to figure out the true reasons of the crashes.

The design experts consulted indicated that congestion on the off-ramp may back up to the freeway which tended to cause rear-end crash. In this case, the signal timing at the intersections at the end of the off-ramp should be adjusted.

Segment 99

Segment 99 is at Tropicana Ave. on the southbound of US 95. The shoulder on this segment is narrow and was identified to cause more crashes on this segment. There were 11 crashes occurred on this segment, of which three were rear-end, and six were non-collision. It was observed by the design experts consulted that the traffic from the on-ramp would merge to freeway and cause congestion on the mainline. In this case, ramp metering is suggested on this on-ramp. It is realized that six on-collision crash is significant, and effort needs to make to find the true reasons for these crashes.

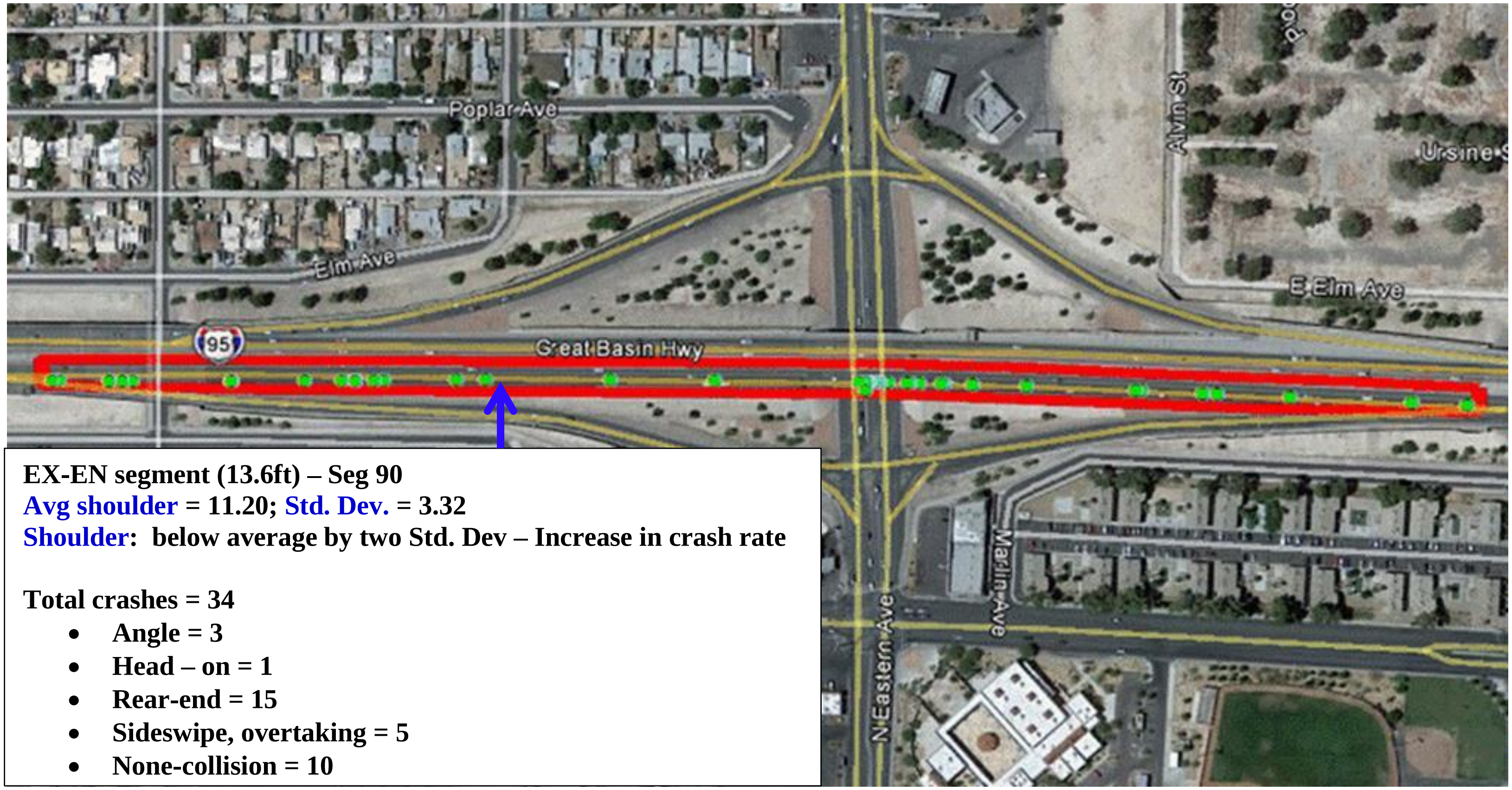
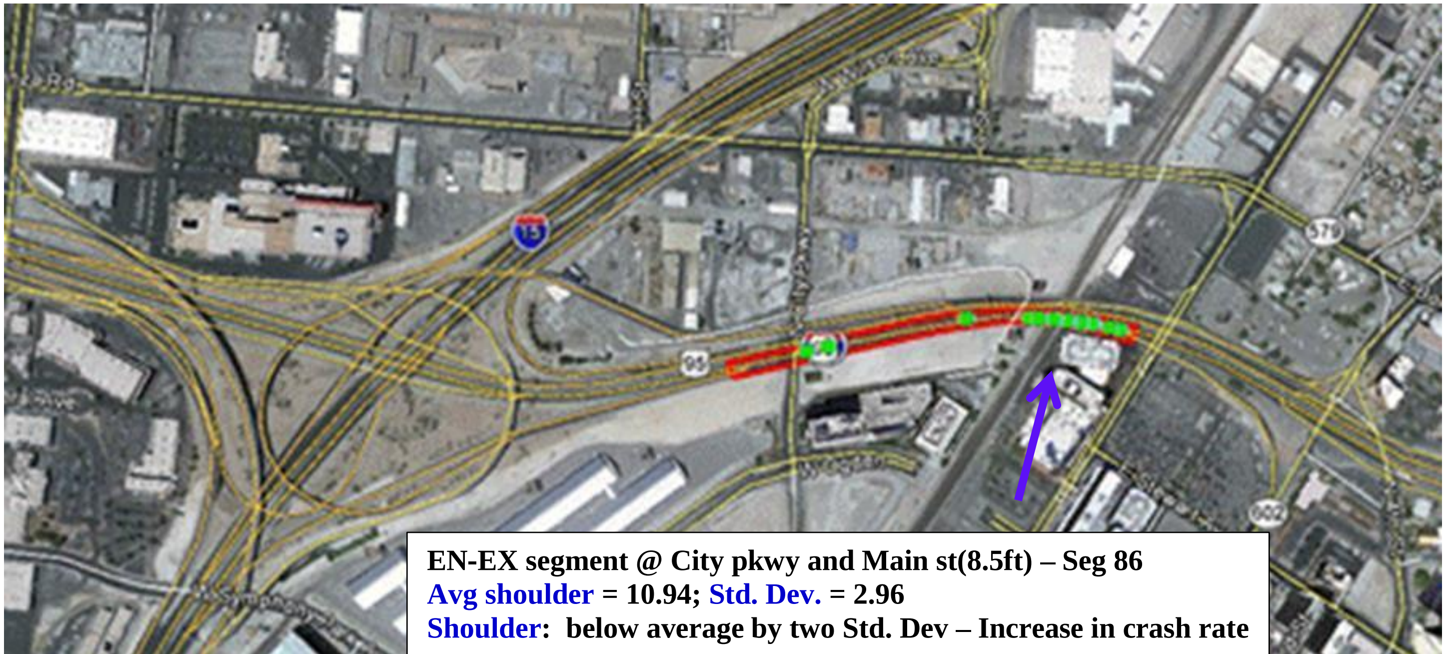


Figure 6.15 Segment 90

Segment 90

Segment 90 is at Eastern Ave. on southbound of US 95. The shoulder on this segment was narrow. The modeling results imply that the narrow shoulder would have contributed to the occurrence of the crashes on this segment. The crash data reveal that there were 15 rear-end crashes and 10 non-collision out of 34 crashes. The data also show that there was more crashes occurred when the pavement surface was wet and during peak hour period.

It was discussed in consulting with the design experts that traffic at this segment tended to drive fast since there are more traveling lane than the segments upstream. At the same time, more traffic moved out of the on-ramp which merged into the mainline and thus caused congestion. This congestion would force traffic slow down and thus cause rear-end crashes. Ramp metering on the ramp was suggested to regulate the traffic into the freeway. It has been noticed that there are significant number of crashes that were non-collision. Efforts need to make to find the true reasons for these crashes. Also, many crashes happened when it rained. Countermeasures to prevent crashes in raining should be developed at this segment.



EN-EX segment @ City pkwy and Main st(8.5ft) – Seg 86
Avg shoulder = 10.94; Std. Dev. = 2.96
Shoulder: below average by two Std. Dev – Increase in crash rate

Total crashes = 19

- **Angle = 4**
- **Rear-end = 9**
- **Sideswipe, overtaking = 2**
- **None-collision = 4**

Figure 6.16 Segment 86

Segment 86

Segment 86 is the first segment after the spaghetti bowl on the southbound of US 95, ending at the off-ramp to the Casino Center Blvd. The traffic from the west side of the spaghetti bowl goes through this segment. These two traffic streams, one from the spaghetti bowl, and the other from the west, are heavy and weave significantly at this segment. The traffic on the off ramp usually cannot clear the ramp quickly, which make the queue on the ramp to spill back to freeway. Since this segment is also relative short, the congestion from the off-ramp would move to the on-ramp. These congesting conditions would cause rear-end crashes which comprise half of the 19 crashes happened on this segment. This situation may have contributed more to the crash occurrence than narrow shoulder does.

The design experts suggested that signage could be used to alert drivers of the congestion on this segment, which could be a way to prevent crashes. More importantly, it was suggested to redesign this section to separate the traffic streams that weave at this segment.

The identified countermeasures for these segments are listed in Table 6.5 and 6.6, and summary is provided in the conclusion chapter.

Table 6.5 EN-EX Segments

Seg #	Location	Countermeasures suggested
	I-15	
18	Northbound I-15 at Sahara Ave.	Separating weaving movement spatially. Neon project.
35	Northbound I-15 at Lamb Blvd	Add additional lane if needed
	I-215	
34	Airport connector on the Eastbound I-215.	Add lanes, build a flyer from the airport to eastbound I-215
51	Westbound I-215 between Decatur Blvd and Jones Blvd	N/A
2	Gibson Rd. on Eastbound I-215	Ramp metering
13	Westbound I-215 between Valle Verde Dr. and Green Valley Pkwy	N/A
	US 95	
86	First segment after the spaghetti bowl on southbound of US 95	Signage for congestion, redesign section of spaghetti bowl to separate weaving
102	Russell Rd. on the southbound of US 95	Install signs to alert speeding to reduce crash occurrence
98	Upstream before the Tropicana interchange on the southbound of US 95	signal timing at the intersections at the end of the off-ramp should be adjusted

Table 6.6 EX-EN Segments

Seg #	Location	Countermeasures suggested
I-215		
23	Eastern Ave. on the westbound of I-215	Ramp metering, change ramp from tapered type to parallel type, install warning sign of congestion
16	Green Valley Pkwy on eastbound I-215	Install ramp metering on ramp at Green Valley Pkwy and St. Rose
52	Jones Blvd on the eastbound of I-215	Install signage to warn speeding
68	Russell Rd. on the eastbound of I-215.	N/A
84	Sahara Ave. on eastbound I-215	N/A
4	Gibson Rd on eastbound I-215	Adjust signal timing at Gibson Rd.
35	Airport connector at westbound of I-215	Build elevated structures to separate weaving traffic
64	Durango Dr. on eastbound I-215	Install signs to alert drivers of speeding
US 95		
90	Eastern Ave. on southbound of US 95	Install ramp metering on on-ramp, prevent crashes in raining
99	Tropicana Ave. on the southbound of US 95	Install ramp metering on-ramp.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effect of primary geometric factors to the occurrence of crashes on freeways in the Las Vegas metropolitan area in Southern Nevada. Multiple linear and probit regression models were calibrated for crash rate and severity for two freeway segment types: EN-EX and EX-EN. GIS and Google map tools were used in collecting crash, geometric and other relevant data. Geometric variables used in this study included number of through lanes on the main facility, length of segments, curve radius within the segments, medians, and shoulders.

Modeling results

Based on analyzing the results, it can be seen that the distinct characteristics of these two segment types determine that they have different factors influencing crash rate and severity. In general, the following observations on safety performance of EN-EX and EX-EN segments in terms of geometric elements can be summarized below.

EN-EX Segments

The geometric factors influencing crash rate on EN-EX segments are number of lane, shoulder and median width, segment length and curvature. Because I-15, I-215 and US 95 are different in many aspects of geometric conditions, some of these factors are significant only on some of these freeways, but not others. Among these five geometric factors, segment length and curvature did not have any influence on crash severity. In other words, number of lane, shoulder and median width determine crash rate and the severity, while segment length and curvature only have influence on the rate to occur crashes, but not the severity of crash after they occurred.

EX-EN segments

Different from the case of EN-EX segments, among the five geometric factors, segment length did not influence crash rate on EX-EN segments. Instead, AADT is the additional factor that influences crash rate. These differences were caused by the distinct characteristics EX-EN segment comparing with EX-EX segments: high traffic volume caused congestion to migrate from EN-EX segments to EX-EN segments. Among the four geometric factors that influence crash rate, only the number of lanes, shoulder and median width influenced both crash rate and severity. Segment curve did not influence crash severity. Because of the unique characteristics of I-15, I-215, and US 95, the impact patterns of these factors on crash rate and severity on individual freeways are different.

Geometric problems and countermeasures

EN-EX segments usually appear before and after an EX-EN segment on a diamond interchange. On an EN-EX segment, congestions usually occur in the following two situations.

First, weaving would happen between traffic streams on to freeway and that off from freeway. Either of these two traffic stream become heavy, the freeway would become congested, which need separating them spatially. The cases at the airport connector on the eastbound of I-215 and the first segment after the spaghetti bowl on southbound of US 95 are examples for this situation. When the traffic from the on-ramp is heavy, ramp metering can be installed, which is a way to mitigate congestion and reduce crash on freeway. The segment after the Gibson interchange at the southbound of I-215 is this situation.

Second, if the traffic on the off-ramp could not be clearly quickly, the queue would back up to freeway and then make the freeway congested. In this case, signals at the end of the off-ramp need to be adjusted to make the off-ramp traffic cleared on a timely manner. If this segment is long, warning signs would be recommended to warn motorists of the congestion downstream. The cases at the segment before Tropicana Ave. and the segment after Russell Rd. on the bound of US 95 belong to this situation.

An EX-EN segment is usually at the middle of an interchange, one side for traffic getting off freeway and the other side getting on freeway. The congestions usually occur in the follows two situations.

First, the traffic on to freeway become heavy, making the merging on freeway congested, and this congestion would quickly spill back to this segment. In this case, it is suggested to install ramp metering. The cases at Eastern Ave. on the westbound of I-215, Green Valley Pkwy on eastbound I-215, and Eastern Ave. and Tropicana Ave. on southbound of US 95 belong to this case. When the traffic is extremely heavy, separating the traffic on to the freeway spatially from that goes through the downstream segment is necessary. This is the case on the Airport connector on the westbound of I-215. If this segment is long, warning signs are suggested to install on this segment, alerting the motorists of the congestion downstream. This is the case for the segments at Eastern Ave. on the westbound of I-215, and Jones Blvd and Durango Dr. on the eastbound of I-215. It is particularly important to the segment at Eastern Ave. because the segment is on a curve. It is important to the segments at Jones Blvd and Durango Dr. because the speeds before traffic reach to these segments are high.

Second, if the traffic getting off the freeway become heavy, congestion on the off-ramp would back up to the freeway, which would create traffic turbulences for traffic even after passing the point of off ramp. This is the case for the segment at Gibson Rd. on the eastbound of I-215.

Future Study Needs

There are some observations that are worthwhile to be further investigated. First, the geometric variable: number of through lanes, influence either the crash rate or severity differently among these three freeways. It increased crash rate on I-15, decreased crash rate on I-215, and did not show any significant impact on crash rate on US 95. This inconsistence needs to be investigated in depth.

Second, the safety performance of EN-EX segments and EX-EN segments are highly correlated because traffic congestion usually moved from one type of segments to another. Thus, the modeling of crash rate or crash severity should consider these two types of segment jointly, not in a manner to mix them up blandly, but in an pairing-up fashion. In other words, these two types of segments around an interchange should be grouped in modeling for simultaneous consideration.

Third, the crash data shows that significant number of crashes happened when the pavement was wet, almost at any locations on the freeway. Investigation should be conducted to identify the type of crashes happened when it was raining or snowing. Countermeasures to prevent crashes in these weathers may need to be identified for implementation.

Fourth, significant number of non-collisions crashes happened. With this issue, it is very hard to identify the cause of crashes, and then as a consequence, it is hard to develop countermeasures. To fully uncover the causes of crashes, this study suggests recording the videos of crashes when they happen. Technologically it is possible to record the crashes that happen in the view of cameras that are installed on the freeway systems. It is also legally feasible for universities to record such videos.

Fifth, the errors in the data collected in this study may influence the modeling results. Most of the data including number of lane, lane width, shoulder width, median width, curve and grade are collected using goolge map. It is recognized that the goolge map is projection of three dimension image. The projection may distort the view of the road feature, which makes the measurements based on vision observation of google map are not accurate. This issue makes it necessary to develop a geometric database from which the measurements of such geometric features can be extracted easily. It is perceived that developing such a uniform database is feasible. At the same time, it is recognized that road geometric features on highway network changes every years and the changes can happen at different times. Capturing such changes is challenging. In addition, extracting geometric features from as-built design file is tedious.

Six, the impact of geometric features on crashes can also be recognized from the profile of freeways and crashes happened. For example, the median and shoulder on I-215 are wide, which may tend to encourage speeding, one of primary causes of crashes. The curves on the EX-EN segment at Eastern Ave. on westbound of I-215 and the EX-EN segment at Durango Dr. on the eastbound of I-215 are obviously have certain influence on the crashes happened on these segments. The length of segments at Gibson Rd. on eastbound of I-215, the segments at Jones Blvd on eastbound of I-215 seemingly contributed to the occurrence of crashes. The critical issue is how to code and measure the curves and present them in modeling.

Seven, it is important to include traffic flow and capacity of the ramps at the two ends of a segment, whether they are EX-EN or EN-EX type. It is because that they determine the extent of weaving in one segment and the one next to it.

Eight, it is important to include the pattern of traffic flow on a segment to show its impact to crashes. AADT is an average value that cannot reflect the fluctuation of traffic. Intuitively, it is the fluctuation of the flow in the peak and no-peak time periods that is directly relevant to the occurrence of crashes. The FAST data may contain certain errors that made it hard to include them in the modeling. Thus, it is important to improve the traffic data quality for modeling safety.

Nine, the approach to identify the geometric problems of freeways may need to be improved. There are a few segments that have high number of crashes happened, but they are not included in pool of segments identified through the modeling approach. It might be due to the fact that the factors that influence the occurrence of crashes on these segments are not part of the variables considered in the modeling. Looking into these segments missing in the pool can help to identify additional factors influence crash occurrence.

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