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# Safety evaluation of freeway exit ramps

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Safety Evaluation of Freeway Exit Ramps

by

Hongyun Chen

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science in Civil Engineering  
Department of Civil and Environmental Engineering  
College of Engineering  
University of South Florida

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Hypothesis Test, Generalized Regression Model

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## **DEDICATION**

This work is dedicated by my dearest parents, Zongxiang Chen and Jinfang Xie.

## **ACKNOWLEDGEMENTS**

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# **SAFETY EVALUATION OF FREEWAY EXIT RAMPS**

**Hongyun Chen**

## **ABSTRACT**

The primary objective of the study is to evaluate safety performances of different exit ramps used in Florida and nationally. More specific, the research objectives include the following two parts: (1) to evaluate the impacts of different exit ramp types on safety performance for freeway diverge areas; and (2) to identify the different factors contributing to the crashes happening on the exit ramp sections. To achieve the research objectives, the research team investigated crash history at 424 sites throughout Florida. The study area includes two parts, the freeway diverge area and the exit ramp sections. For the freeway diverge areas, exit ramp types were defined based on the number of lanes used by vehicular traffic to exit freeways. Four exit ramp types were considered here including single-lane exit ramps (Type 1), sing-lane exit ramps without a taper (Type 2), two-lane exit ramps with an optional lane (Type 3), and two-lane exit ramps without an optional lane (Type 4). For the exit ramp sections, four ramp configurations, including diamond, out connection, free-flow loop and parclo loop, were considered.

Cross-sectional comparisons were conducted to compare crash frequency, crash rate, crash severity and crash types between different exit ramp groups. Crash predictive models were also built to quantify the impacts of various contributing factors. On the

freeway diverge areas, it shows that Type 1 exit ramp has the best safety performance in terms of the lowest crash frequency and crash rate. The crash prediction model shows that for one-lane exit ramp, replacing a Type 1 with a Type 2 will increase crash counts at freeway diverge areas by 15.57% while replacing a Type 3 with a Type 4 will increase crash counts by 10.80% for two-lane ramps. On the exit ramp sections, the out connection ramps appear to have the lowest average crash rate than the other three. The crash predictive model shows that replacing an out connection exit ramp with a diamond, free-flow, and parclo loop will increase crashes counts by 26.90%, 68.47% and 48.72% respectively. The results of this study will help transportation decision makers develop tailored technical guidelines governing the selection of the optimum design combinations on freeway diverge areas and exit ramp sections.

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background

Freeways play important roles in the highway system around the country. In the United States, the interstate highway system, which composes less than 2% of the total urban highway mileage, carries more than 20% of the traffic by the end of 2006. Freeways provide the specific traffic facility which allows the traffic run smoothly in the roadway network at the highest level. They are constructed according to the highest highway design standards and regulated public movements by full controls of traffic elements such as capacity, post speed, geometrics fundamentals, and level of service.

Exit ramps are the only control accesses used for traffic exiting freeways. They also serve as transitions from freeways to secondary crossroads which could be freeways, major or minor arterials, or local streets. The design of freeway exit ramps could significantly impact the safety and operation performances on freeways, exit ramps and crossroads. The AASHTO Green Book (A Policy on the Design of Geometric Highways and Streets) (12) mentioned that complex design components make ramps vary from simple to comprehensive layouts so that each ramp site should be studied and planned carefully. Freeway diverge areas are the specific segments that divide the freeway traffic exiting from or continuing on the freeway mainlines. Freeways connect with exit ramps



by several different diverge types called exit ramp types in this study. These types cause different results of safety performances on the freeway diverge areas by different ways. Exit ramp section is another important concern in this study. Exit ramps provide limit-accesses from freeways to other freeways, lower-speed arterials or local streets. A few factors, such as geometrics, traffics, and local conditions, have different relationships with crashes. These facts include more than deceleration distances, exit ramp lengths, design speeds, operating speeds, speed differences, exit ramp configurations, or road conditions. Better understanding the relationships among them would help improve the safety, efficiency, mobility, accessibility, and accommodation aspects for both freeway diverge areas and exit ramp sections. “Ramp Management and Control Handbook”(14), published by U.S. Department of Transportation (DOT) and Federal Highway Administration (FHWA) in 2004, aims to manage ramp policies, strategies and technologies as to improve safety on the exit ramp and the influential areas. Ramp management strategies control the flow vehicles exiting a freeway not only on the exit ramps, but also on the freeway neighboring areas. A before and after evaluation of ramp crashes in Minneapolis found that the number of peak period crashes on freeways and ramps increased 26% when there was no ramp control strategy in 2001. This case revealed the reality that resolutions to the deficiencies on the freeway diverge areas and exit ramp sections can help to improve safety.

Successful managements on the two research segments, freeway diverge areas and exit ramp sections, could obtain benefits on society, economics and cultures and gain satisfactions on safety improvements. However, the impacts of exit ramp types on the safety performance of freeway diverge areas have not been well studied or documented

until recently. Few have focused on the impacts of the types of exit ramps concerning the lane balance problems such as the number of lanes used by traffic to exit freeways. The details of the relationship between the lane balance and safety are not well understood. Since the limited work that has been performed, a few tentative conclusions might be drawn. It can be assumed that potential improvements will lead to fewer crashes, thus enhance safety on the freeway diverge areas. On the exit ramp sections, the various influential factors on the safety performance at entire exit ramp sections need to be revised and re-conducted since previous studies have a few limitations. For example, some predictive crash models concerned different ramp configurations and ramp length, however the control types of ramp terminals did not contain in these models (3). Some models combined the off ramps and on ramps. The combination might ignore the dissimilar operating factors between the two different kinds of ramps.

Several types of exit ramps are used for traffic to exit freeways on the diverge areas. The increasing vehicular crashes in freeway diverge areas lift up the need to select the best exit ramp designs to improve safety on freeway diverge areas. The problem is relatively new and highly demanded in today's highway system. For the exit ramp sections, little focus has been put on the safety issues in the State of Florida. So this study would conduct comprehensive crash comparisons and analyses on freeway exit ramp sections for the whole state. The results of two research parts, freeway diverge areas and exit ramp sections in this study, will help transportation decision makers develop tailored technical guidelines governing the selection of the optimum exit ramp types and combinations of related factors to be used on our freeway diverge areas and exit ramp sections.

## **1.2 Research Subject**

On the freeway diverge areas, the most commonly used freeway exit ramps include two-lane exit ramps with an optional lane, two-lane exit ramps without optional lane, single-lane exit ramps with widening to two lanes on the ramp beyond the exit gore, and three basic number of through lanes changed to two through lanes with one lane reduced and designated as the exit lane. Drivers exiting a freeway must decrease vehicle speeds and weave to the deceleration lane toward the entrance of the exit ramp. Different types of exit ramps require drivers to make distinctive decisions to complete related maneuvers both for exiting and continuing with the freeway. As a result, different exit ramp design may impact the safety and operational performance of freeway diverge areas in different ways. On the exit ramp sections, different ramp configurations such as diamond, out connection, free flow, and parclo flow and other factors such as widening lanes, pavement paintings, and terminal controls might confuse drivers as well. These mixed influential features on the exit ramp cause existing problems and situations more multifaceted. This study processes to quantitatively evaluate the safety features of two issues.

### **1.2.1 Freeway Diverge Areas**

None of the studies for the past two decades focused on the lane balance problems on the freeway diverge area which directly connects the mainline segment to exit ramps. AASHTO Green book defines the lane balance as the number of approach lanes on the highway after the exit should equal to the number of lanes on the highway beyond the exit, plus the number of lanes on the exit, minus one. The fundamental arrangement of a

freeway segment is the designation of the basic number of lanes which should be consistency along the freeway. The basic number of lanes might be added or deleted where the traffic volumes increase or decreased at some degrees. On the freeway diverge area, part traffic on the freeways beyond the exits leave the freeway and so that the volumes change in this segment. The one or two outer lanes may drop to the exit lanes so that the number of lanes on the freeway mainline sections did not balance ahead of or after the exits. This would not only cause confusions for the exiting vehicles but also for the continuing vehicles on the freeways. The lane-balanced and unbalanced exit ramps require drivers take different maneuvers. Even considering the lane balanced exit ramps or the unbalanced exit ramps respectively, different numbers of exit lanes on the freeway segments have different characteristics as well. The study would focus on the lane balance issues which are innovated and original in the freeway exit ramps studies.

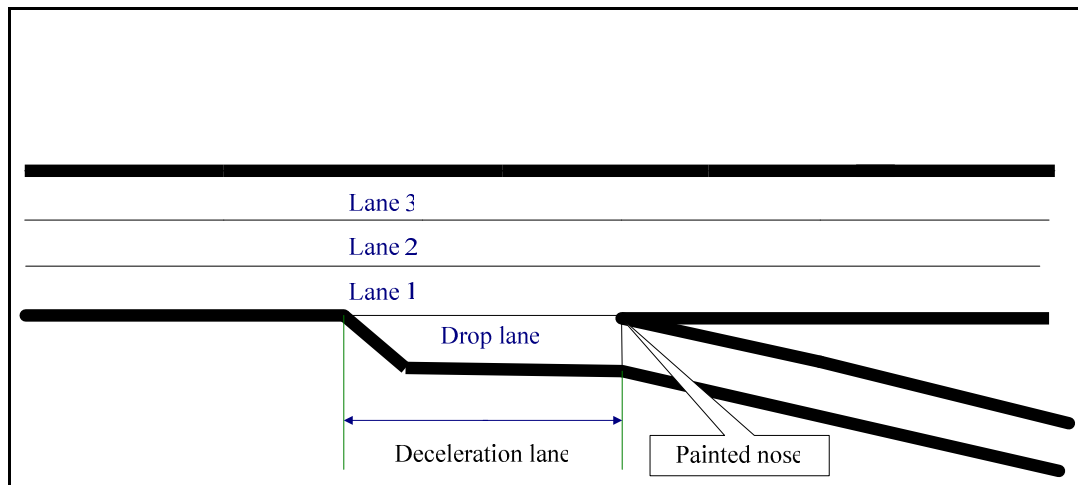
The exit ramp type is defined by the number of lanes used for traffic to exit freeways. They could be single-lane exit ramps or two-lane exit ramps. After reviewing the sites in the whole Florida interstate highway systems, expressways, turnpikes and parkways, four types are used frequently for the state. So four different groups based on the types of exit ramps are characterized for the study. For convenience, they were set as Type 1 exit ramps (Type 1), Type 2 exit ramps (Type 2), Type 3 exit ramps (Type 3) and Type 4 exit ramps (Type 4) respectively. The definitions of each type of exit ramp are described below and illustrated in Figure 1 through Figure 4 below.

1) Type 1 exit ramp — Parallel from a tangent single-lane exit ramp shown in Figure 1:

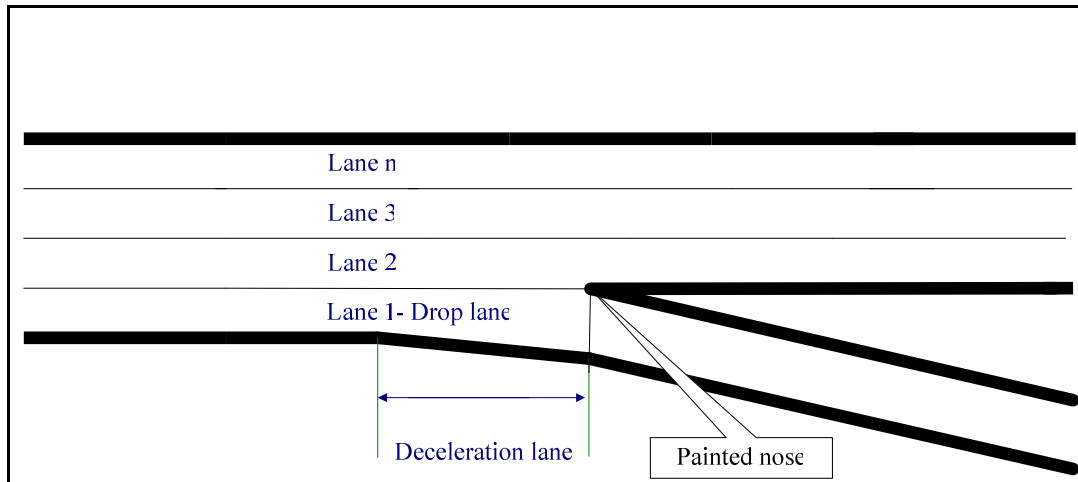
It is a full width parallel from tangent that leads to either a tangent or flat exiting curve which includes a decelerating taper. The horizontal and vertical alignment of

- type 1 exit ramps were based on the selected design speed equal or less than the intersecting roadways. No direct drop lanes on the mainline sections beyond or after exits. The outer lane with a tangent would be a drop lane to the exits and become the through lane on the exit ramp section.
- 2) Type 2 exit ramp — Single-lane exit ramp without a taper shown in Figure 2: This type is when the outer lane becomes a drop lane at the exit gore forming a lane reduction. A paved and striped area beyond the theoretical gore were present at this type of exit ramps to provide a maneuver and recovery area. No additional lane was added when compared with Type 1.
  - 3) Type 3 exit ramp — Two-lane exit with an optional lane shown in Figure 3: This type includes two exit lanes while a large percentage of traffic volume on the freeway beyond the painted nose would leave at this particular exit. An auxiliary lane to develop the full capacity of two lane exit was developed for 1500 feet. The entire operations in this type of exit ramps took place over a significant length of the freeway in most cases. The outer one of the two exit lanes directly drops to the exit ramps. But the inner lane of the two exit lanes, which is an optional lane, has two alternatives by continuing on the freeway or running off the freeways.
  - 4) Type 4 exit ramp — Two-lane exit without an optional lane is shown in Figure 4: It is used where one of the through lanes, the outer lane, is reduced and another full width parallel from tangent lane developed with a taper is also forced to exit. It differs as from Type 3 exit ramps as Type 4 exit ramps do not enclose the optional lane.

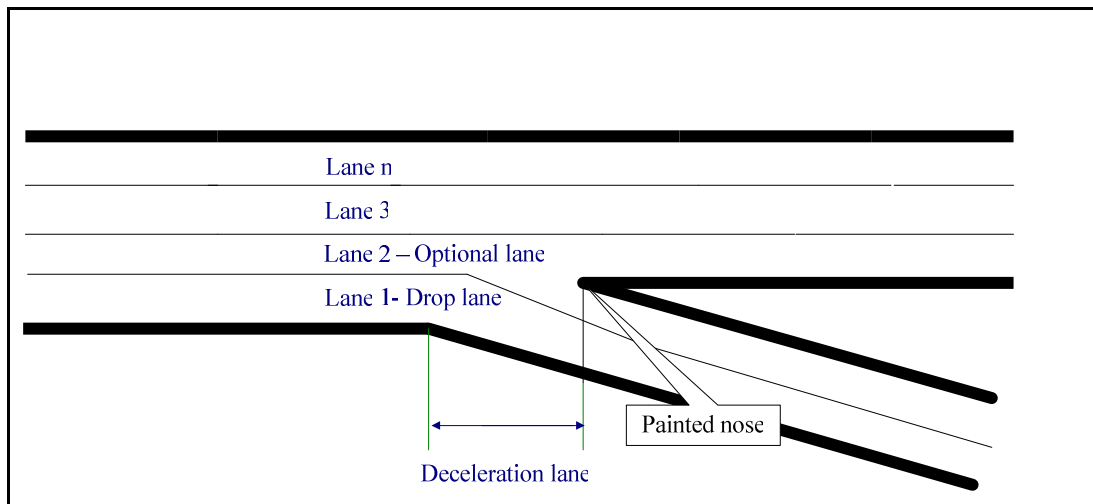
From the figures, they indicate that Type 1 and Type 3 are lane balanced ones while Type 2 and Type 4 are lane unbalanced exit ramps. In practice, there is a type 5 exit ramp which is a two-lane exit ramp without optional lane and without a taper, which is not widely used in Florida and the samples we found are too small to draw defensible conclusions.



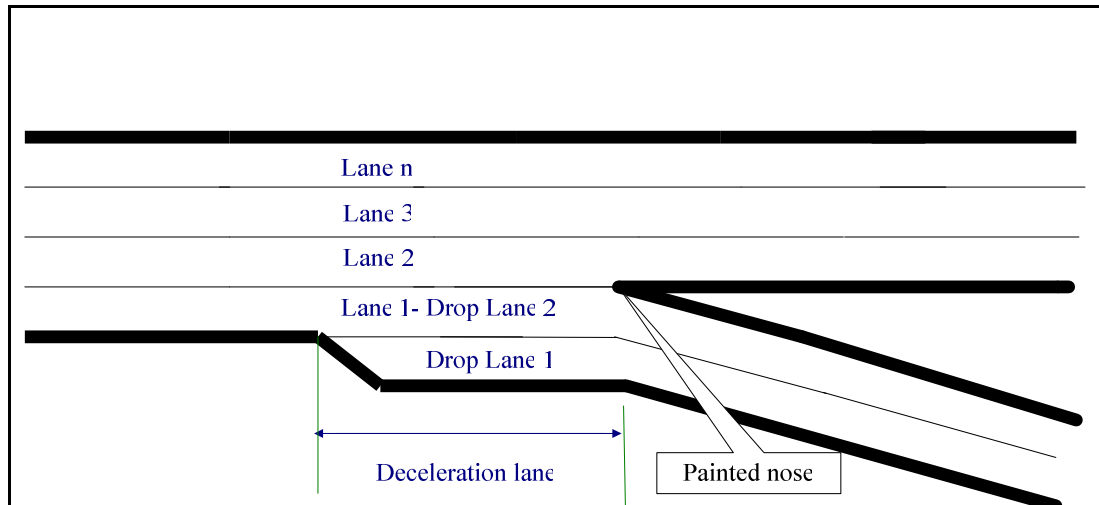
**FIGURE 1. Type 1 Exit Ramp: Parallel from a Tangent Single-lane Exit Ramp**



**FIGURE 2. Type 2 Exit Ramp: Single-lane Exit Ramp without a Taper**



**FIGURE 3. Type 3 Exit Ramp: Two-lane Exit Ramp with an Optional Lane**



**FIGURE 4. Type 4 Exit Ramp: Two-lane Exit Ramp without an Optional Lane**

### 1.2.2 Entire Exit Ramp Sections

The entire exit ramp section from the beginning of pointed nose, which diverge the freeways and ramps, to the end of ramp terminal is another research concern. This study is to acquire an adaptable, practical, and integral transition system from the freeway to the secondary crossroad. Ramp designing contains many possible influential factors such as ramp configurations, ramp design speed, lane numbers, ramp terminal control types, ramp length, or ramp curvatures.

Ramp configurations are usually considered as the ramp types in the previous studies. Bauer and Harwood's (3) analyses show that diverse ramp configuration designs have significantly dissimilar impacts on the safety performance especially for off ramps. Typically various configurations accommodate to the ramp sites by the features of site locations. In order to clearly indicate the safety performance with related parameters, the ramp configuration was considered one of them. Four widely used configurations in Florida are identified in the study. They were briefly defined as diamond exit ramps, out



connection exit ramps, free-flow loop exit ramps and parclo loop exit ramps. From Figure 5-A to Figure-D illustrate the four ramp configurations which describe the shape of ramps in simplified modes.

Figure 5-A is a diamond exit ramp which is a one-way road with both left and right turnings at terminals. Figure 5-B is an out connection exit ramp which only supplies the single turn at the ends of exit ramps.

Figure 5-C and 5-D are two classic loop ramps that make at least 270 degrees of turning movements to the secondary roads. Free-flow loop ramps are designed as full cloverleaf ramps with or without collector or distributor roads on the ramp segments. The parclo loop exit ramp is a partial cloverleaf ramp which has a preference to provide an arrangement setting the right exiting vehicles. This configuration could give either one or two turning ways at the exit terminals while the exit ramps' location meets the requirements to provide enough design radii, space, curvatures and related geometric criteria.

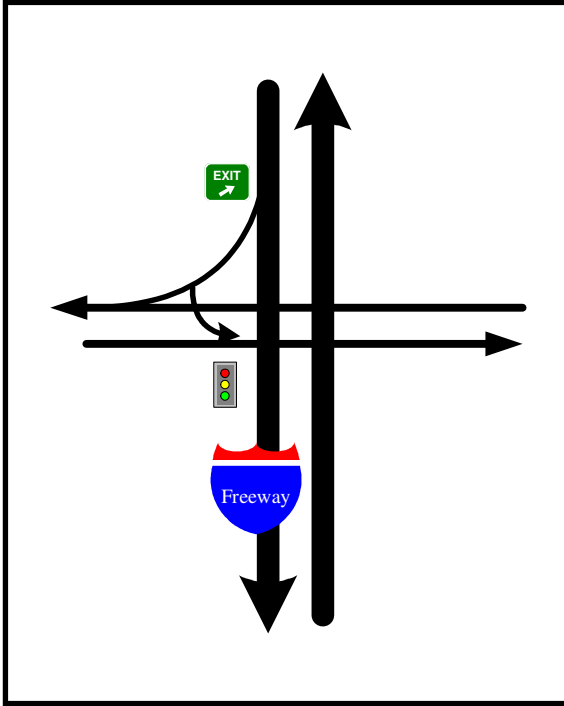


Figure 5-A. Diamond Exit Ramps

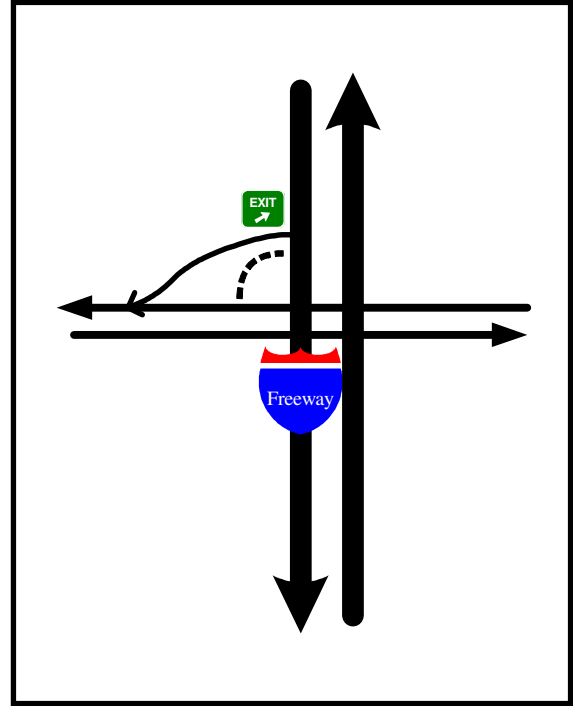


Figure 5-B. Outer Connection Exit Ramps

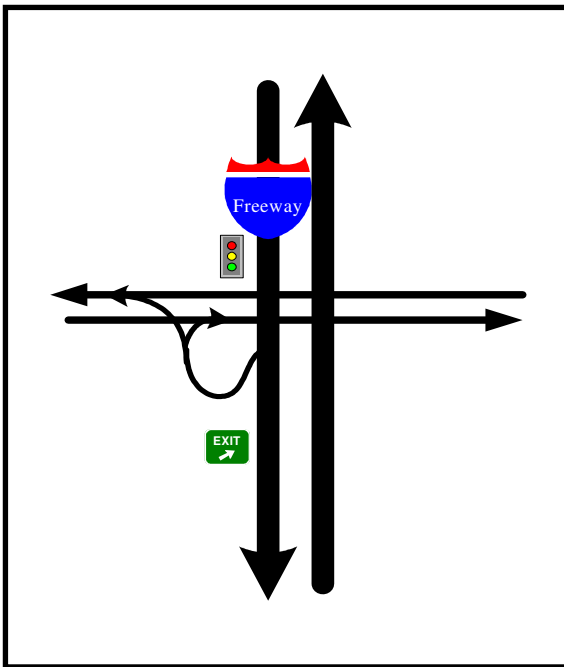


Figure 5-C Free-flow Loop Exit Ramps

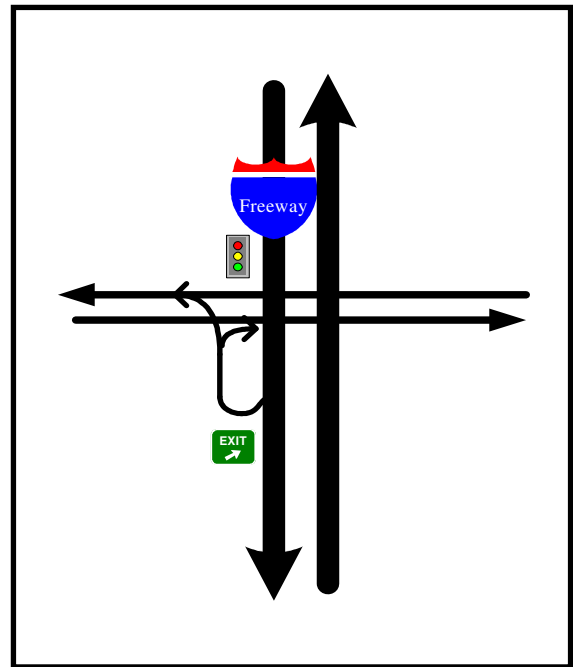


Figure 5-D Parclo Loop Exit Ramps

FIGURE 5. Typical Four Exit Ramp Configurations

### **1.3 Research Objectives**

The objective of the study is to evaluate safety performances of different exit ramps used in Florida and national. The research objectives can divide into two parts. The first one is to evaluate how the impacts of different exit ramp types on the safety performance of freeway diverge areas. The second one focuses on identifying the different factors contributing to the crashes happening on the exit ramp sections. This study developed quantitative evaluations and comparisons on the freeway diverge areas and exit ramp sections accordingly.

Statistical analyses among four types of exit ramps on the freeway diverge areas, parallel from a tangent- single-lane exit ramp, single-lane exit ramp without a taper, two-lane exit ramp with an optional lane and two-lane exit ramp without an optional lane, are conducted. The four different ramp configurations and other parameters on the entire exit ramp sections are examined as well to find their effects on the safety features for the entire exit ramps. Base on the result in this study, it would be a way to judge what kind of geometric, traffic, and combinations of the correlated conditions have the best safety performance on the freeway diverge sections and entire exit ramp sections. This is also a practical step to guide the methods of safety improvements on freeway diverge areas and exit ramp sections. The results could also be applied in design guidelines, handbooks or research projects.

### **1.4 Research Approach**

Previous studies were revised and potential safety measurements for this study were selected. Crash histories at selected freeway segments were investigated and crash

data were collected. Cross-sectional comparisons were conducted to compare the safety impacts the two segments of freeway diverge areas and exit ramp sections respectively. On the basis of the collected crash data for the diverge areas, statistical analyses were conducted to quantitatively evaluate the impacts of different types of exit ramps on the safety performance of freeway diverge areas and different ramp configurations on exit ramp sections. In addition, crash prediction models were developed to identify the factors that contribute to crashes at selected sites. The results of this study will help transportation decision makers develop tailored technical guidelines governing the selection of the optimum exit ramp to be used on our freeways and recommend the optimal design characteristics both on the diverge areas and the entire exit ramps.

### **1.5 Research Tasks**

In order to achieve research purposes, following tasks were made to obtain rational conclusions. Existing methods and technologies were gathered to reach the goals of two research subjects. Possible applications were identified the in the research fields. After summarizing these potential measurements, useful method from previous studies were selected and detailed developments were conducted for this study. These methods and developments need to be feasible to perform and practice. The analysis process should be correct and reasonable. The results base on this study can be applied to other exit ramp managements. In this study, four steps containing ten main tasks were categorized to well organize the research procedures as following:

1) Step 1:

- Task 1: Literature Search and Review;
- Task 2: Field Observation;

- Task 3: Field Operation Plan;
- 2) Step 2:
- Task 4: Site Selection;
  - Task 5: Field Data Collection;
  - Task 6: Data Reduction;
- 3) Step 3:
- Task 7: Data Analysis;
  - Task 8: Research Results;
- 4) Step 4:
- Task 9: Conclusions and discussions;
  - Task 10: Final Report.

Step 1, classifying the first three tasks, mainly focused on going over the past safety performance measurements and methods, discovering the possibility of the potential applications, viewing sites, building up study purposes and arranging work plans. Step 2, from task 4 to task 6, gathered the site data and arranged them to do the further analysis. This step is a very tough and tedious one since the study needs large sample sizes to get reasonable results and all the related data need to be found at available methods. The third step applied the main approaches to conduct safety evaluations procedures. The final step concluded the research findings and summarized the whole research study in the final report in the thesis. These four steps contained all the needed tasks for this research study and have been proved successfully in past projects.

## **1.6 Thesis Outline**

This thesis contains six chapters, one reference part and one appendix section at all. Chapter 1 provides an overview and the research objective for the study. Chapter 2 presents a brief description of previous study and related topics for the research subjects

in order to acquire an advanced study. Chapter 3 summarizes the techniques applied in this project, which included a detailed description of the proposed methods and basic concepts using in data analysis procedure. Chapter 4 describes the procedures of site data collection and reduction. Chapter 5 presents the procedures of crash analysis, results of crash investigation and impacts of selected variables. The final chapter, Chapter 6, emphasizes the summaries, conclusions and recommendations from this study to assist other agencies, public works, engineers better understanding the safety issues of the freeway diverge areas and entire exit ramp sections. The list of references follows the final chapter and one appendix lists the sample site photos for the research subjects to illustrate different exit ramps applied in the State of Florida.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

This chapter summarizes previous studies and findings related to the project. Two parts, diverge areas on the freeway mainline sections and entire exit ramp sections, consist of the study subjects are discussed respectively to describe the integral evaluations of the previous discoveries in the research field.

#### **2.1 General Freeway Guidelines**

Freeways provide the primary transportation networks and roadway systems by achieving the highest functional hierarchy of highway systems by design purposes. The grand reliance on the facilities requires safer and more efficient implements on existing freeways and their related infrastructure systems to improve the safety performances.

The AASHTO Green Book (A Policy on the Design of Geometric Highways and Streets) (12) designs the key requirements on the highway facilities such as the ramps, interchanges and frontage roads. In order to accommodate high traffic demands of safety on freeways, exit ramps and secondary crossroads, designing proper handlings of freeways and ramps are essential in the highway systems. Many factors impacts safety performances on freeways and their adjacent facilities. Also, the crash is a direct index on safety evaluations. The wide variety of site geometric conditions, traffic volumes,

highway types, and design layouts could eliminate or increase conflict points at some degrees while crashes related to conflict points at some levels.

During the past several decades, some design regulations mentioned the importance of safety performance of freeway diverge areas and exit ramp sections. Current state and national literature reviews include freeway and ramp management handbooks, guidelines of optimal geometric designs from Highway Capacity Manual and AASHTO, reports from National Cooperative Highway Research Program (NCHRP) and Different State Departments of Transportation, proceedings from Transportation Symposium, papers from transportation engineering journal, etc. Additionally, useful books and publications were also collected to do analysis in the project and current rules, regulations, standards, and practices in Florida were evaluated and summarized for the two research subjects in the sequent sections.

## **2.2 Freeway Diverge Areas**

During the past several decades, though some studies have mentioned the freeway exit ramps, none of them focused on the impacts of the number of lanes used by traffic to exit freeways. Closely reviewed the literature, there is little direct paper or evaluation in safety performance of diverge areas which has been researched before. In previous studies, ramp types are usually defined by ramp configurations such as diamond, loop, directional, outer connector, and other instead of the lane balance issues for the diverge sections. Though many design handbooks and guidelines focused on the relationships of geometric elements and collision causes, they did not mention the influence of lane balances on the freeway diverge areas.



In 1969, Cirillo et al. (9) did a purely innovative investigation on the traffic crash study on the interstate system for that period. They found that the relationship could be established between fatality crashes and geometric elements. The geometric factor included several types of interchanges, paved shoulders, sight distance, delineators, surface types, and other variables. After about thirty years, Garber and Fontaine (7) developed a guideline given name as “Guidelines for Preliminary Selection of the Optimum Interchange Type for a Specific Location” to search the operational and safety characteristics for the optimal ramp design. The newest instruction is the ITE “Freeway and Interchange Geometric Design Handbook” edited by Joel (17) in 2006. The handbook focuses on geometric and operational characteristics of freeways and interchanges. The book recognized that geometric design procedures for freeways and interchanges may vary. It also provides the evidence that is valued as an accompaniment of the AASHTO Greenbook (12), the Highway Capacity Manual (HCM) (13), and Traffic engineering Handbook 5<sup>th</sup> Edition (16).

In 1998, Bared et al. (1) developed a generalized regression model known as Poisson Model to estimate the crash frequency for the deceleration lanes plus the entire ramps as a function of ramp AADT, mainline freeway AADT, deceleration lane length and ramp configurations. The ramp configurations considered in that study include diamond, parclo loop, free-flow loop, and outer connector. The model showed that the crash frequency on freeway ramps increased with the ramp and freeway AADT and decreased with the increase of the deceleration lane length. A 100 ft increase in deceleration lane length will result in a 4.8% reduction in crash frequency. The coefficients of the model also indicated that off-ramps suffered from more crashes as

comparing to on-ramps. However, this study did not consider the number of lanes using for traffic leaving freeways. This problem is essential in the driving behavior because the balanced lanes and unbalanced lanes require drivers to take different operating manners.

Later, Bauer and Harwood (3) built up several regression models to determine the relationships between traffic accidents, highway geometric design elements and traffic volumes. The statistical modeling approaches used in the research included Poisson and Negative Binomial regressions. It was found that the ramp AADT explained most of the variability in the crash data report at selected sites. Other variables found to be significant in crash prediction models contained freeway AADT, area type (rural, urban), ramp type (on, off), ramp configurations, and lengths of ramp and speed-change lane (deceleration lanes, acceleration lanes). Other models have been built to find out the functions of different variables in different kind of models. The independent variables are crash frequencies on the speed –change lanes, entire ramp sections, the selected ramp sections, and speed change sections plus the entire ramp sections. The best fit model was the one that combined crash frequency for the entire ramp, together with its adjacent speed-change lanes. The significant influential factors included area type, ramp type, ramp configurations (diamond, loop, outer connector, others), length of speed-change lanes, and length of the entire ramps. Another main finding is that models for the total crashes achieved much better than those for the only fatal and injury crashes. The models combined the on ramps and off ramps, and acceleration lanes and decelerations lanes. Off ramps usually occur more crashes than on ramps as mentioned before; the requirements for the length, curve, and design guidelines of acceleration length and deceleration lanes vary; ramp configurations could not be the ramp types on the diverge areas. Without

judging these factors, models would decrease the accuracy of the conclusions, narrow the applications of the results and could not disclose the real situations. But this study provided reasonable methods such as the regression models which have been proved strappingly employed in the safety studies (11, 19, 25, 26, 27, 28, and 31).

One main program is called Highway Safety Improvement Program (18) that can help states decrease the number of crashes and provide optimal ways for arranging, applying, and estimating safety plans. From side to side of the introduction, all correlated issues to improve highway safety are recognized, measured, implemented and evaluated highway planning, designs, constructions, maintenances, and operations. Moreover, past studies emphasized the safety evaluation based on previous mentioned methods such as regression models or statistical tests that have been proved as useful methods in the safety studies. Following paragraph listed the wide applications of these methods.

Sarhan et al. (11) designed the approach to help achieving the optimum predictive models. The model related to the length of acceleration and deceleration lanes based on expected collision frequency. Joanne and Sayed (25) undertook the study to quantify the relationship between the design consistencies on the roadway safety. The generalized linear regression approach is used for model development as a quantitative tool for evaluating the impact of design consistency on road safety. Garcia et al. (19) analyzed different deceleration lengths as functions of exit trajectory types, speeds, and localization. Munoz and Daganzo (26) predicted the queued length at a wave speed about 13 mph in congested traffic by KW model. This method is widely used in the safety evaluation of intersections as well as freeway sections. Maze et al. (27) analyzed the TWSC expressway intersection for crash rates, crash severity rates and fatal crash rates

by Poisson regression models. Keller et al. (28) divided crashes by different types as angle, left-turn, head-on, rear-end and pedestrian/bicycle by linear regression models while speed limits were found to be important. Bernhard et al. (31) ranked the locations and the estimated benefits of improvement by assigning fatal, injury and PDO crashes. Hypothesis tests were conducted with normal distribution with high number of crashes and Poisson distribution with a low number of crashes. The statistical tests were usually employed to find crash-prone sites in identifying some sites as hazardous at some a particular level of confidence. In fact, the level of confidence is that 100% minus the Type I error. Type I error is the percentage that mistakes the safety sites for hazardous sites. Another Type II error is the percentage that mistakes the hazardous sites for safety sites. They concluded that the program would benefit to public traffic to make the possible efforts in order to improve the safety studies.

Other studies focus on revealing the geometric, traffic, or related influential values to the mainline sections separately. Rakha and Zhang (20) modeled a total of 34 different weaving sections to estimate the traffic volume at weaving sections including merge and diverge areas at the appropriate boundaries on freeways. The paper demonstrated that the volume estimated by the model had a significant effect on drivers' behavior in the mainline weaving sections. Abdel-Aty et al. (22) tested various speed limits to evaluate the safety improvement on a section of Interstate 4 in Orlando, FL. Real-time crash likelihood was calculated based on split models for predicting multi-vehicle crashes during high-speed and low-speed conditions. The improvement was proved in the case of rising medium-to-high-speed regimes on the freeway. The paper recommends that the speed limit changes upstream and downstream should be large in

magnitude (15mph) and implemented within short distances (2miles) of the diverge locations. It makes obvious that speed limit have some specific effects on the collisions from the upstream to downstream of diverge areas on the freeways. Cassidy et al. (24) noticed the problem that queuing from the segment's off-ramp spilling over and occupying its mandatory exit lane comes up frequently. The situation delayed the mainline vehicles as well and would increase weaving conflicts. Janson (8) examined the relationship of ramp designs and truck accident rates in Washington State plus a comparison to limited data from Colorado and California. The paper grouped freeway truck accidents by ramp type, crash type, and four conflict areas of each diverge ramp. The crash data were compared for these groups on the basis of number of truck crashes per location and per truck-mile of travel. The conclusion is slight different from generally belief that a ramp with a lower accident rate per truck trip due to low truck volumes may still be a high-risk site. But these results could not represent the real conditions if applied to all the passenger cars. The higher crashes number might still be constant with high volume since truck volume is really low and have the specific feats itself.

One research study, concerning on the number of lanes used by traffic exiting freeways was conducted by Batenhorst (10). The paper, "Operational Analysis of Terminating Freeway Auxiliary Lanes with One-Lane and Two-Lane Exit Ramps: A Case Study", used three simulation software packages, the Highway Capacity Software (HCS), CORSIM and Simtraffic on the operational analysis of weaving area at twenty locations by the level-of-service. The range of traffic and geometric conditions among the twenty sites varied. The findings of the case study suggest that a one-lane exit ramp may afford the best traffic operations apart from weaving length. The experience gained from

the case study is to give support to traffic engineers to design efficient freeway facilities and to help researchers understanding the operational effects of geometric design. Even though this study considered exit lane numbers on the freeway diverge areas, the better level-of- service could not necessarily stand for better safety performance, and these two might have opposite results in some cases.

Based on the studies mentioned before, the impacts of exit ramp types on the safety performance of freeway diverge areas have not been well studied or documented until recently. Several previous studies have evaluated the safety impacts of different ramp configurations such as diamond, loop, directional, outer connector, and other. However, these studies have not considered the lane balanced problems on the diverge areas to regulate the number of lanes that shall be used for traffic to exit freeways.

### **2.3 Exit Ramp Section**

The entire exit ramp section is another concern in this study to provide a comprehensive evaluation of the safety performance on freeway exits. Ramps are all one-way roads with one or more legs at terminals to connecting secondary crossroads. Different involvements of design speeds, configurations, speed differences among freeway and ramp section, ramp lengths or the direct connection features determine different exit ramps which have dissimilar safety effects. Some studies have focused on exit ramp sections and prior conclusions were described below.

Lord and Bonneson (2) calibrated predictive models for different ramp configurations at 44 selected sites. The ramp design configurations addressed in this study included diagonal ramps, non-free-flow loop ramps, free-flow loop ramps, and

outer connection ramps. The non-free-flow (parclo flow loop) ramp experienced twice as many accidents as other types of ramps Bauer and Harwood (3) as mentioned before modeled the Negative Binomial regression model on the entire ramp section as well and concluded that diamond ramp have slight less crash frequency comparing to other ramp types when other influential variables remain constant. At the same year, Khorashadi (4) used another method known as ANOVA test to forecast the relationship among ramp configurations, geometry parameters and crash frequencies. This study found that the geometric elements had much weaker impacts than the ramp configurations. McCartt et al. (6) examined 1,150 crashes occurring on heavily traveled urban interstate ramps in Northern Virginia. The three major common crash types, run-off-road, rear-end, and sideswipe, accounted for 95% of total crashes. The countermeasures mentioned in the study included increasing ramp design speed, increasing curve radii, installing surveillance systems such as detectors, cameras, and advanced message signs.

Abdel-Aty and Huang (21) explored an origin-destination survey to customers on the central Florida's expressway system. The distance traveled to exit a ramp did not depend only on the spacing between ramps, but also on other factors, such as the trip purpose, vehicle occupancy, driver's income level, and E-Pass implementation when the vehicle was equipped with an electronic toll collection system. A main finding was that the guide signs beyond the expressway exits had an important impact not only on unfamiliar travelers but also on the experienced drivers. Though it was a little counter-intuitive, the result shows different design features on diverge areas would have an effect on familiar drivers as well. Hunter et al. (23) conducted field observations on speed relationships between ramps and freeways by videotaping. Notable conclusions were

drawn that vehicle speeds on exit ramps were much higher than the post speed limit. Since the big difference between the ramp post speed limit and operating speed, some unfamiliar drivers might slow down the speed while some familiar drivers might enter the exit ramp at a high speed relative far above the limit speed. That might be a vital reason why rear-end crashes account a large percent of crashes in the ramp sections.

Some studies focused on the connections between different influential factors which could be the ramp volumes, configurations, crashes, curvatures, and so on. These studies comprised Newell's (29) "Delays caused by a queue at a freeway exit ramp", Shaw and Mcshane's (30) "Optimal Ramp Control for Incident Response", and Hunter et al.'s (34) "Summary Report of Reevaluation of Ramp Design Speed Criteria". Newell clarified that the graphical solution is more clearly illustrating practical issues. Shaw and Mcshane attended to optimize some measurements on the crashes to minimize the crash disruption. Hunter et al.'s concluded that ramp design speed should larger than 50% of freeway speed. This conclusion accommodated to Hunter et al.'s (23) result that operating speed on the exit ramp is higher than the post speed limit.

It is obvious that many studies defined ramp configurations as ramp types. The conclusions included that free-flow ramps have more crashes than others, increasing ramp volume might increase crashes, the post speed limit on the ramp has some impacts on both local/familiar drivers or unfamiliar drivers and the operating speed is usually much higher than the post speed. Even several useful results are made on the exit ramp sections, but few consider the following two issues in the safety effects, ramp terminal treatments and ramp lane changing named widening on the exit ramp segment. Widening in this study is defined as the number of lanes changing after the pointed nose or in the



middle of the entire ramp. The definition of ramp terminal treatments in “Ramp Management and Control Handbook” is those can be implemented at ramp/arterial connections as to better manage traffic exiting the ramp facility. They normally solve the specific problems that occur at the ramps or arterials. Diverse terminal control strategies have the potentials to affect operations on the exit ramp and adjacent arterials. Ramp terminal treatments implemented at exit ramps could reduce queue spillback from the secondary roads, decrease the potential for collisions on the freeway at the back of the queue, and improve traffic flow and safety on or near ramp facilities. Typically four strategies are broadly employed, signal timing improvements, ramp channelization, geometric improvements, and signing or pavement markings improvements.

The advantages of using ramp terminal strategies are to better coordinate with ramp terminal signal timing, to offer sufficient storage space either for left turn or right turn vehicles and to accommodate consistently on both exit ramps and secondary crossroads. The method of signal timing adjustments aims to prevent queue spillback to the freeway facility beyond exit ramps. Ramp channelization can increase capacity, supply enough storage space or a separate lane adjacent to the broad-spectrum lane, and delineate separate traffic movements. Geometric improvements manage sight distances, horizontal and vertical curves, and any other geometric deficiencies. Signing and pavement marking improvements deal with guiding motorists of downward conditions and facilitating vehicle movements. Implementations of ramp terminal treatments reducing delay and queuing length, decreasing conflict points, enhancing safety and minimizing impact both on upstream and downstream highways and arterials. The functions vary by implemented treatments. Alternatively, negative impacts with different

terminal treatments varied by the each site. Those might increase trip length, cause supplementary travel time, or extend queuing and signal delay. Accordingly, different terminal control designs or different combinations of terminal designs might have various powers on the safety aspects of entire ramp sections. Retting et al. (32) endeavored to reduce urban crash rate by building potential countermeasures to the five most common crash types in fourteen cities. For the vast combinations of the crashes about (69%-81%) in each type via dissimilar cities, the author suggested that signal timing, sign visibility, sight distances would be the improvement measure to enhance safety in general solutions.

This study would consider the terminal control methods to expose the impacts of terminal control types on safety. One study conducted by Bared et al. (5) comparing crashes between single point and tight diamond ramps related crashes on the cross road only. Single point diamond interchange is diamond ramp free-connects to the cross roads No triangle median occurs at the terminals. Tight diamond interchange differs to single point diamond interchange since there is a triangle median separation at the termination to split different traffic movements for left turns or right turns. Crash data were subtracted from 27 tight diamond sites and 13 single point sites in Washington to build a Negative Binomial model of total crashes on the exit ramp and cross-road flow. However, the safety comparison did not reveal a significant difference between the two types of interchanges for total crash. This study only compared one terminal treatment as ramp channelization; however the sites number here is not sufficient enough to do a regression model. The lanes widening is another issue as one of the strategies in the exit ramps. Several ramps from the field observations show that it will wide to two or more lanes after the pointed noses which separate the freeway mainline sections and ramp sections.

## **CHAPTER THREE**

### **METHODOLOGY**

This chapter describes the selected methodologies which would be applied in this research study. The principles for selecting the main methods concern on how the functions are, whether they are practical or easily applied to the data base, and what the potential results are. The research subjects included two parts defining as freeway diverge areas and entire ramp sections separately. After reviewing prior studies, guidelines, handbooks and related researches, useful methodologies and important parameters are identified for the safety analysis. The main approaches used included the cross-sectional comparison method, hypothesis tests, and generalized regression models.

#### **3.1 Crash Frequency and Crash Rate**

Crash frequencies or crash rates are two indicators that are generally used in the safety studies to compare different treatments or groups. This research project would calculate both of them for further analysis.

##### **3.1.1 Crash Frequency**

Crash frequency is the real number of crashes that have happened at a certain location or segment in a particular time or time interval. It is commonly used for several

benefits. Firstly, the crash data are easy to get and simple to calculate. Next, the meaning behind is straightforward so that governmental officials, engineers, and public could understand it readily. The third virtue is that it could represent diverse selected places in one parameter and could change directly while the selected lengths or vicinity of the segments changed. The resource of the noticed crashes is only from police long form crash report which describes specific features for each crash. Florida Traffic Crash Analysis Report (CAR System) provides detailed crashes and updates the database each year.

The mathematics mean value of crash frequency is labeled as the average number of crashes. With different groups or managements, the average number of crashes was calculated based on the number of sample sites. In statistical assumption, the mean value normally is the most proficient estimator for the population groups. The following equation defines the average crash number with a specific group, C, as:

$$C = \frac{\sum_{i=1}^n c_i}{N} \quad (1)$$

Where,

C=average number of crashes for the sites with a particular group;

$c_i$  = number of crashes at site i in the group;

N = total number of sites within the group.

For the diverge areas, four exit ramp types are classified so that four groups were chosen to compare the mean values of crash frequency. Besides, three additional values stand for the accuracy and variations of the mean values. The median value is the middle rate in a series of data that have been ranked in order to scale and part the sites into two

identical fractions. The maximal and minimum values are the largest and smallest crash number in a specific group. The four additional variables imply the variation of the each sample and the mean values. If the median value is much larger or smaller than mean value, the distribution curves of crash number indicate biasness in the judgment. In order to get reasonable mean value, usually the four values, mean, median, maximum, and minimal are calculated respectively to represent the distributions of the number of crashes.

### 3.1.2 Crash Rate

In this study, crash rate is defined as crashes per million vehicles per vehicle miles traveled for a specific section. Crash rates are used as a criterion for more truthful for segments under the same geometric and traffic conditions to narrow the impacts of these important factors. The crash rate,  $r$ , for a particular freeway segment can be calculated in the following formula:

$$r = \frac{1,000,000 \times A}{365 \times T \times V \times L} \quad (2)$$

Where,

$r$  = crash rate at a freeway segment (crashes per million vehicles per mile);

$A$  = number of report crashes (crashes per year),

$T$  = number of years;

$V$  = average daily traffic volume (vehicles per day);

$L$  = length of the freeway segment (miles).

It is believed that the crash frequency tends to increase as the average daily traffic (ADT) goes up even through many other factors affecting the situation. In this study, the corresponding ADT for each site was obtained from annual Florida traffic information

CDs. The time frame is determined for the database in continuous years when site characters have not been changed in the period. The average crash rates, which are the arithmetic means of crash rates, were calculated for the four groups in the freeway diverge areas. The statistical assumption is similar to the average number of crash as mentioned before. The average crash rate,  $R$ , is defined as:

$$R = \frac{\sum_{i=1}^n r_i}{N} \quad (3)$$

Where,

$R$  = average number of crashes rates with a particular group;

$r_i$  = number of crashes rates at segment  $i$  in the group;

$N$  = total number of sites within the group.

The median, maximal, and minimal values are measured as well to observe the distributions of crash rates.

### 3.2 Crash Type and Crash Severity

Since the objectives are to estimate the safety impacts among 4 exit ramps on diverge area and along the entire exit ramp sections, the total number of crash, crash severity, and crash types having the highest percentages to the total crashes were chosen for each group. Crash severity that is widely used in the safety analysis can be classified to two categories: PDO (Property-damage-only) and injury/fatal crashes.

### **3.2.1 Crash Type**

In the crash database maintained by FDOT, crash type is defined by the first harmful event of at-fault vehicles. The comparison of crash types will help to identify driver behaviors that are related with the types of exit ramps. A total number of 40 crash types are concluded in the Florida's CAR system. The most three highest crash types occur on diverge areas are rear-end crash, side-swipe crash and angle crashes. Rear-end crash and side-swipe crash counted for about 60% of total crashes, 46% rear-end crashes and 16% side-swipe crashes. The target crash types on the exit ramp sections are rear-end crash, angle crash and side-swipe crash as well.

Rear-end crashes which regularly take place while the first vehicle stopped or suddenly slowed down and the following vehicle had a collision with the first vehicle in the rear piece of the vehicle. The severity of these crashes can range from minor to severe depending on the speed of the following vehicle that hits the first vehicle.

Sideswipe crash is another common crash type in this study and usually happens when changing lanes, misdirection of exiting freeway, or vehicle weaving. The severity of this type is also ranged from minor to severe.

The one vehicle crossing the passageway or changing directions in the road might conflict with another vehicle. They are frequently set as angle crashes. Angle crashes are also commonly noticed on the misdirected vehicles. The severity of the crashes usually causes severe crashes than rear-end crashes. Comparing to other types, the three types mentioned above is the most concerned types in this diverge area and exit ramp sections

### **3.2.2 Crash Severity**

Usually, crash severity level is recorded for each police reported crash. Three major levels of crash severity generally defined in the study can be classified to three categories:

- 1) Property-damage-only (PDO) crashes;
- 2) Injury crashes;
- 3) Fatal crashes;

In a property-damage-only crash, only properties are damaged but no person is hurt; in an injury crash, at least one person is lightly hurt because of the crash; in a fatality crash, at least one person is dead within 90 days after the crash which was the most concerned problems in many other studies and this study as well.

### **3.3 Cross-Sectional Comparison Approach**

The cross-sectional comparison analysis is satisfactory to provide adequate and reasonable consequences. It is long believed that cross-sectional approach is a logical and efficient technique of judging the safety effects. The cross-sectional method has been proved valuable and has been performed on a number of prior studies that involved median alternatives, right turns followed by u-turn to direct left turns and truck accidents at freeway ramps. In transportation fields, traffic engineers have experimental judgments as long as the most influential factors such as section length, average daily traffic (ADT), speed, ramp length are well controlled. Cross-sectional analyses to evaluate different treatments are fairly reliable for the results. Briefly, reliable conclusions could be got within this measurement. In other words, this method compares the safety of two



different groups of sites with and without the treatment under investigation. It is necessary to select similar geometric conditions in order to get the reliable results in comparing site histories of different types.

In this study, cross-sectional comparison was conducted to measure freeway diverge areas with different types of exit ramps and exit ramp sections with four configurations. This approach involves comparing crash frequency, crash rate, crash type, and crash severity of a group with a treatment, to that of a group of with other treated sites. As mentioned before, the selected freeway segments were divided into four groups based on the types of the exit ramps. On the basis of the collected crash data, statistical analysis was conducted to quantitatively evaluate the safety impacts of different types of freeway exit ramps.

The major assumption behind this comparison was that all other characteristics in the sites remained the same during the study period. The significant geometric and control factors considered in this study included deceleration length, ramp length, average daily traffic(ADT), posted speed limit, number of lanes in the freeway, surface conditions, shoulder conditions and so on. By comparing crash through statistical testing, conclusions could be reached regarding the relative safe treatment among different treatments.

### **3.4 The Hypotheses Test**

Hypothesis tests are utilized to test whether the observed differences of the selected variables such as mean values, variance values, or proportion values between two or more groups have significantly variation in a statistical term. Assumptions of

observing the sample data were calculated in the hypothesis testing to measure the suppositions whether they have under similar features. If the results did not support the assumptions, then the assumed suppositions are considered doubtful. The formula of hypothesis testing includes two competing statistical hypotheses: a null hypothesis ( $H_0$ ) and an alternative hypothesis ( $H_a$ ). The null hypothesis is a postulation that one parameter of a population is true under sufficient statistical terms. The contrast postulation of the null hypothesis is an alternative hypothesis. It is assumed that all the other situations that did not covered by the situations under null hypothesis.

The test result is to reject or fail to reject the null hypothesis under the specific conditions based on the statistical distributions while they reply upon Z, t, F or  $\chi^2$  distribution. The decision of whether rejecting the null hypothesis is based on the statistic value range on the statistical distribution mentioned before at a statistical term named as the significant level  $\alpha$ . Typically the level of confidence as  $1 - \alpha$  is applied to determine the statistical confidence instead of  $\alpha$ . The procedures of conducting a hypothesis test including four steps:

1) Step 1: Select Null Hypothesis-  $H_0$ ,

Select an Alternative Hypothesis -  $H_a$ ;

2) Step 2: Determine the level of confidence  $(1 - \alpha) * 100\%$ ;

3) Step 3: Calculate the statistical value;

4) Step 4: Compare the statistical value to the critical value on the distribution, and decide to reject or fail to reject the null hypothesis  $H_0$ ;

The following two parts describe the detailed procedures to conduct hypothesis tests on the equality of two means and the proportionality analysis.

### 3.4.1 Hypotheses on the Equality of Two Means

Mean values of two different populations were tested to get reasonable conclusions whether to reject or not reject the null hypothesis. The average crash numbers and rash rates from one group to another group were examined if they are significantly different. Assumed that two populations say  $X_1$  and  $X_2$ , where  $X_1$  has an unknown mean  $\mu_1$  and known variance  $\sigma_1^2$  and  $X_2$  has an unknown mean  $\mu_2$  and known variance  $\sigma_2^2$ . The purpose is to test whether the two populations have the same mean  $\mu_1$  and  $\mu_2$ . The first step is to build the null hypothesis  $H_0$  and an alternative hypothesis  $H_a$ :

$$H_0 : \mu_1 = \mu_2 \quad (4)$$

$$H_a : \mu_1 \neq \mu_2 \quad (5)$$

The procedure is based on the fact that the difference in the sample mean,  $X_1$ ,  $X_2$ , of two populations of interest with a sample size of  $n_1$  and a sample size of  $n_2$  separately,

$\bar{X}_1 - \bar{X}_2$  will fit the normal distribution of:

$$\bar{X}_1 - \bar{X}_2 \sim N(\mu_1 - \mu_2, \sigma_1^2/n_1 + \sigma_2^2/n_2) \quad (6)$$

The second step is to choose the level of confidence. In this study 90% is used and  $\alpha$  equals 10%. The third step is to calculate the statistical value  $Z_0$  ( $n \geq 25$ ) or  $t_0$  ( $n < 25$ ):

$$Z_0 = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \quad (7)$$

$$t_0 = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_p^2 \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}} \quad (8)$$

The final step is to compare the calculated value with the critical value  $Z_{\alpha/2}$  or  $t_{\alpha/2}$ . The null hypothesis could be rejected if:

$$Z_0 > Z_{\alpha/2} \text{ or } Z_0 < -Z_{\alpha/2} \quad (9)$$

$$t_0 > t_{\alpha/2} \text{ or } t_0 < -t_{\alpha/2} \quad (10)$$

If the variance  $\sigma^2$ , is unknown, it can be replaced by the square of the standard deviation of the sample size  $n$  which is  $S^2$  as following:

$$S^2 \equiv \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n} \quad (11)$$

If the sample sizes is less or equal to 25, the populations are approximately t distribution with a pooled variance,  $s_p^2$ , based on sample variance  $s_1^2$  and  $s_2^2$ . The formula is given by:

$$S_p^2 \equiv \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \quad (12)$$

### 3.4.2 Hypotheses Tests on the Proportionality Analysis

On the basis of the collected crash data, statistical analysis was conducted to quantitatively evaluate the crash type and crash severity on the safety effects. The proportionality hypothesis test was utilized in this study to comparing target crash types and crash severity between different freeways diverge sections.

Proportionality test is often used to test the significance of the percentages between two populations or samples. Let  $p_1$  and  $p_2$  be the proportions of a particular type of crashes in two different groups. Assuming that the total crash counts in these two groups are  $m$  and  $n$  respectively, for testing the null hypothesis:

$$H_0: p_1 = p_2 \quad (13)$$

Versus

$$H_1: p_1 \neq p_2, \quad (14)$$

$H_0$  can be rejected if:

$$Z = \frac{|p_2 - p_1|}{\sqrt{\frac{p_2(1-p_2)}{m} + \frac{p_1(1-p_1)}{n}}} \geq Z_{\alpha/2} \quad (15)$$

### 3.5 Statistical Predictive Model

Crash prediction models were developed for this study at selected freeway segments and entire ramp sections respectively. The purpose to use regression predictive models is to identify the factors that contribute to the crashes and quantify the effects on crashes at selected sites. This research project would draw on the generalized linear regression models to mold crash number.

Generalized linear models have been widely used for modeling crashes at safety studies (1, 3, 11, 19, 25, 26, 27, 28, and 31) at intersections, roadways or freeways. Generalized linear models are the expansion forms of the classical linear regression models. The classical linear regression model assumes that the dependent variable is continuous and normally distributed with a constant variance. The assumption is not appropriate for crash data which are approximately Poisson distributed and are generally non-negative, random and discrete in nature. Numerous previous studies have suggested the use of Poisson models or Negative-Binomial (NB) Models for modeling crash data (1, 3). The Poisson model assumes that the dependent variable is Poisson distributed. Using

a Poisson model, the probability that a particular freeway segment  $i$  or an exit ramp section experiences  $y_i$  crashes during a fixed time period is given by:

$$p(Y_i = y_i) = p(y_i) = \frac{\mu_i^{y_i} e^{-\mu}}{y_i!}, \quad i = 1, 2, 3, \dots, n \quad (16)$$

Where,

$\mu_i$  = the expected number of crashes for segment  $i$ ;

$y_i$  = the probability that a particular segment  $i$ .

A logarithm link function connects  $\mu$  to a linear predictor  $\eta$ . The link function and the linear predictor determine the functional forms of the crash prediction model. If the linear predictor is a linear function of the explanatory variables, the fitted crash prediction model takes the functional form as below:

$$\mu_i = \exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_k x_{ik}) \quad (17)$$

Where,

$\beta_0, \beta_1, \dots, \beta_k$  = coefficients of explanatory variables;

$x_{i1}, x_{i2}, \dots, x_{ik}$  = explanatory variables.

If the linear predictor is a linear function of the logarithm of the explanatory variables, the functional form is given below:

$$\mu_i = \beta_0 x_{i1}^{\beta_1} x_{i2}^{\beta_2} \dots x_{ik}^{\beta_k} \quad (18)$$

The Poisson model assumes that the mean of the crash counts equals the variance. The assumption is usually too stringent considering the fact that the variance is often greater than the mean. In this condition, overdispersion will be observed and the estimated coefficients of the Poisson model are biased. An alternative to deal with the over dispersed data is to use the negative binomial model. The negative binomial model

assumes that the crash counts are Poisson-gamma distributed. The probability density function of Poisson-gamma structure is given by:

$$p(Y_i = y_i) = \frac{\Gamma(y_i + a^{-1})}{y_i! \Gamma(a^{-1})} \left( \frac{a\mu_i}{1 + a\mu_i} \right)^{y_i} \left( \frac{1}{1 + a\mu_i} \right)^{a^{-1}}, i=1, 2, 3 \dots n \quad (19)$$

Where

$y_i$  = the crash count at segment  $i$ ,

$\mu_i$  = the expected number of crashes for segment  $i$ ,

$\alpha$  = the dispersion parameter.

The dispersion parameter determines the variance of the Poisson-gamma distribution. Usually  $\alpha$  can be estimated either by the Moment Method or by the Maximum Likelihood Method.

Two parameters are often used for evaluating the goodness-of-fit of a generalized linear model. These two parameters are the scaled deviance (SD) and the Pearson's  $\chi^2$  statistic. For an adequate model, the two statistics should be chi-square distributed with  $(N-p)$  degrees of freedom, where  $N$  is the number of observations and  $p$  is the number of parameters in the model. The scaled deviance equals twice the difference between the log-likelihood under the maximum model and the log-likelihood under the reduced model. The scaled deviance can be calculated as:

$$SD = -2(\log(L_\beta) - \log(L_s)) \quad (20)$$

Where

$L_s$  = the likelihood under the maximum model;

$L_\beta$  = the likelihood under the reduced model.

The Pearson's  $\chi^2$  statistic can be calculated as:

$$\text{Pearson's } \chi^2 = \sum_{i=1}^n \left( \frac{y_i - \mu_i}{\sigma_i} \right)^2 \quad (21)$$

where

$y_i$  = the crash count at segment  $i$ ,

$\mu_i$  = the expected number of crashes for segment  $i$ ;

$\sigma_i$  = the estimation error for segment  $i$ .

It is usually assumed that the crash data are approximately normally distributed. Thus, the scaled deviance SD and Pearson's  $\chi^2$  statistic for an adequate model should be approximately chi-square distributed with  $(N-p)$  degrees of freedom, where  $N$  is the number of observations and  $p$  is the number of parameters in the model.



## **CHAPTER FOUR**

### **DATA COLLECTION**

This chapter focuses on illustrating the data collection procedures that include the selected sites and relative sites information. Both freeway diverge areas and entire exit ramp sections are reviewed and the criteria for classifying the site segments and segment lengths are explained. Detailed methods of identifying road sections in FDOT's system, subtracting specific site database, and tackling with the crash data for each site were depicted in this chapter as well.

#### **4.1 Site Selection Criteria**

The study focuses on the safety effects of the freeway diverge areas and entire exit ramp sections. In order to obtain reasonable results, criteria to identify the site segments are really important in order to narrow the unstable and unrelated factors. The criteria were listed below for both freeway diverge areas and freeway exit ramp sections:

- 1) All the objects are on the freeway diverge areas or exit ramps;
- 2) Freeways defined here are the highway segments with the highest level of service and full control of accesses;
- 3) Only right exit ramps are considered in the sites which means all exits should be at the right hand of the directions on freeways;

- 4) The impacts of left exit ramps are not incorporated in this study as they have significant different features to right exits;
- 5) A sufficient and significant curb, bar, or other facilities in the median separates two directions;
- 6) The right-shoulder of freeways and exit ramps should be clear, no sight obstruction, and no dangerous facilities;
- 7) The grade variations are smallest so that no grade varieties are considered in both sections;
- 8) The freeway segments should be homogeneous segments without large horizontal or vertical curves distinctions since this research would narrow the other parameters that not compared;
- 9) All sites are in Florida States from District one to District seven plus an additional Florida Turnpikes generally named as District eight.

Two dissimilar sections are selected so that they both have special requirements for the segments. The following items list the special site requirements at the freeway diverge areas:

- 10) The minimal posted speed limit on the freeway mainline section should be larger than 50 mph;
- 11) The upstream and downstream distances from the deceleration lanes are long enough so that influential factors up or down from the deceleration lanes are minimal;
- 12) Deceleration lanes are calculated from the beginning of the taper or widening points to the painted nose;

13) Four different ramp types on the diverge areas have different number of lanes at freeways, but the research segments remain same.

The exit ramp sections that connect the diverge areas and continue until the beginning of secondary roads should meet subsequent extra criteria:

14) The exit ramp lengths begin from the painted nose and end at the last part of terminals;

15) All exit ramp suggested or post speed limits is larger is 25 than mph no matter the ramp configurations or ramp length.

Following these criteria ensures that the candidate list of field study sites could be obtained without low speed limits in the freeway diverge areas and large difference of speed limits on entire ramp sections. This would make the same characters except the concentration variables to do the statistical analysis. The lane width is an interesting parameter in this study so that the lane widths are not necessarily synchronized in the sites selection procedures. From the field studies, all the preferred segments would go for the interstate highway systems, expressways, turnpikes, and parkways in Florida.

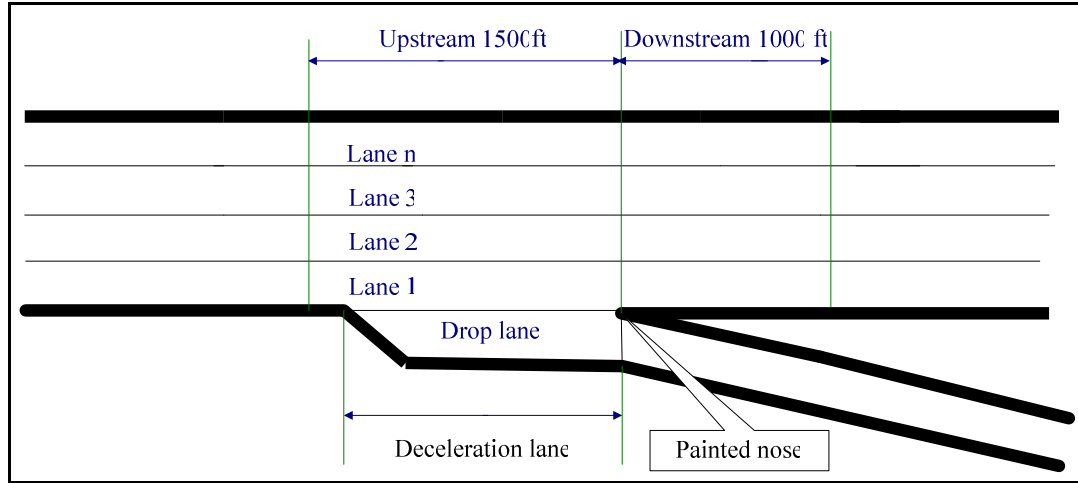
#### **4.2 Segment Length Definition**

Two research sections are defined in this section, the freeway diverge areas and the entire exit ramp sections. The segment length of diverge areas include the deceleration areas and the adjacent vicinities that have related effects for traffic exiting or continuing on freeways. The decision is based on both previous studies and site observation experiences. The exit ramp length includes the entire ramp sections no matter the ramp configurations, ramp terminal control types or other factors. No more regions are taken into concerns as the ramp sections are continuous to the diverge areas.

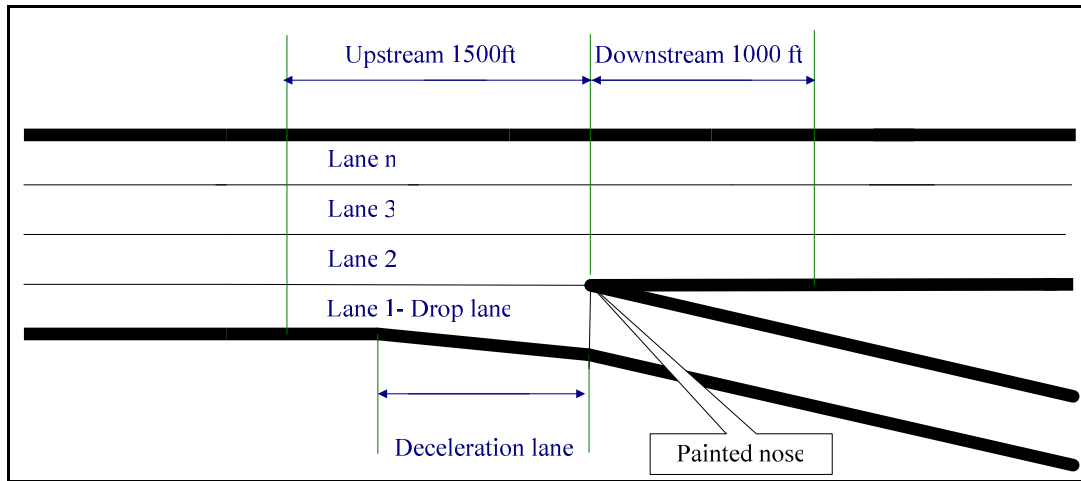
#### **4.2.1 Freeway Diverge Area Length**

The freeway diverge segment in this study is a section of freeway which contains a deceleration lane and its adjacent section. The segment length for the freeway diverge area consists of two continuous sections, including (1) a 1500 ft section located in the upstream of the painted nose and (2) a 1000 ft section located in the downstream of the painted nose. Thus, the length of the freeway diverge segment in this study equals 2500 ft for each site. The definition of the freeway diverge segment for each type of exit ramp is also given in Figure 6 through Figure 9. They illustrate the whole study section that combines the deceleration areas and their surrounding areas.

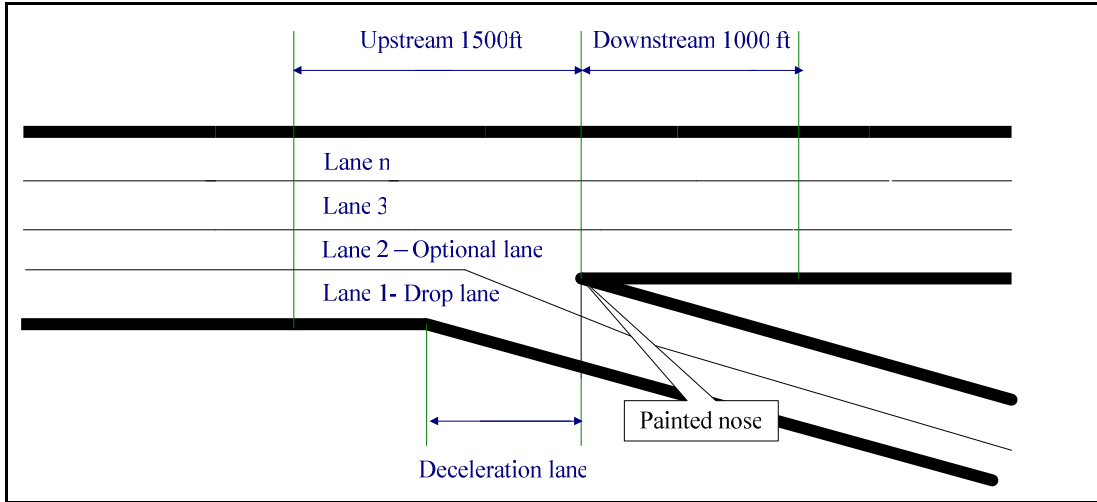
Using different influential distances in the upstream of painted nose could result in different safety analysis results. If the selected distance is too long, crashes reported for selected freeway segments may include some mainline crashes which are not directly related to exit ramps. If the selected distance is too short, however, the selected freeway segment is not long enough to cover the entire influential area of exit ramps. In previous studies, the selected influential distance located upstream of the painted nose ranged from 1000 ft to 2000 ft (1, 11, 12). The HCM (13) suggests 1500 ft beyond the painted nose in the simulation software including Corsim and Highway Capacity Software (HCS). In addition, the length of deceleration lane at selected diverge sites varies from 26 ft to 918 ft. Our field observations show that, when the distance to painted nose is greater than 1500 ft, the exit ramp type does not impact behaviors of mainline drivers in an obvious way. Due to these reasons, a 1500 ft section was selected as the influential area located upstream of painted nose and 1000 ft downstream the painted nose on the freeway mainline sections.



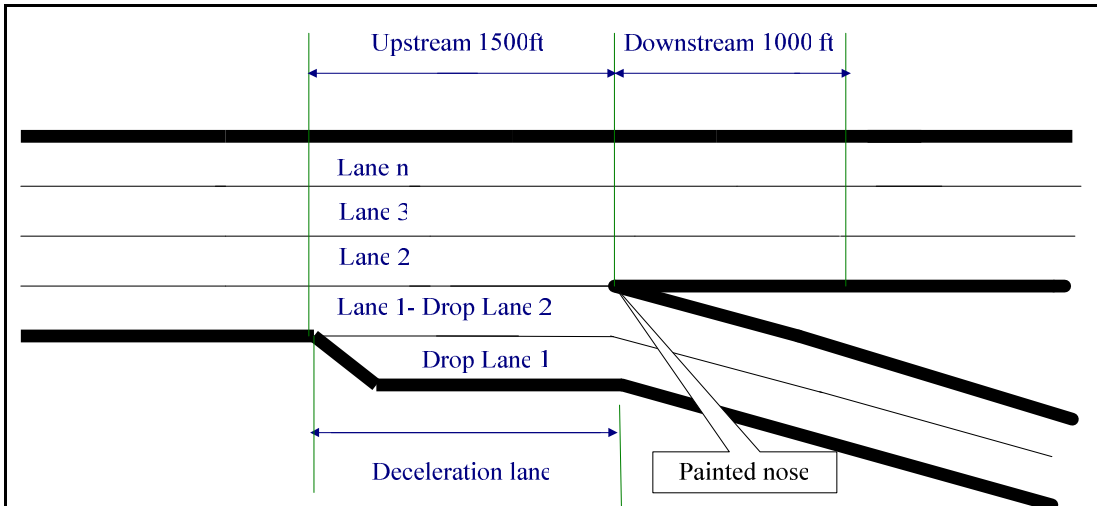
**FIGURE 6. Type 1 Exit Ramp Length: Parallel from a Tangent Single-lane Exit Ramp**



**FIGURE 7. Type 2 Exit Ramp Length: Single-lane Exit Ramp without a Taper**



**FIGURE 8. Type 3 Exit Ramp: Two-lane Exit Ramp with an Optional Lane**



**FIGURE 9. Type 4 Exit Ramp: Two-lane Exit Ramp without an Optional Lane**

#### **4.2.2 Exit Ramp Section Length**

The crash frequency is related to the segment length since different distances might have different effects on the number of crashes when other situations are equal. Usually, longer distances might have more crash potentials than shorter distances. Resende and Benekohal (35) did a comprehensive study on the influence of segment lengths and the geometric variables on crash rates. The paper proved the essences of different segment lengths.

The entire ramp section is the length of the exit ramp itself. The definition means that the painted nose is the beginning of exit ramp and the end of terminals is the closing stages for the exit ramp. It varies slightly from past studies conducted by Lord and Bonneson (2), Bauer and Harwood (3), Khorashadi (4), McCart et al. (6), and Janson et al. (8). Some studies excluded the terminal sections from the entire exit ramps. However, different termination styles would influence the beyond sections as well as the adjacent sections. Some adjusted the exit ramp sections plus the upstream deceleration lanes. This study would separate these two continuous sections because the diverge areas and ramp sections have dissimilar crash features and prominent influential factors. The mixed of these two might get incorrect results. Even Bauer and Harwood (3) did consider the entire ramp sections, they ruled out the all the rear-end crashes for the ramps. It might misrepresent the crash distribution and lead to misunderstand of the other factors to the rear-end crashes which are generally highly occurred in the exit ramps. As a result, the clarity of ramp length here uses the definition described before. The following Figure 10 from A to D present the ramp segment lengths for four ramp configurations as mentioned above.



Figure 10-A. Diamond Exit Ramp Segment Length





**Figure 10-B. Out Connection Exit Ramp Length**



**Figure 10-C. Free-flow Loop Exit Ramp Segment Length**



**Figure 10-D. Parclo Loop Exit Ramp Segment Length**

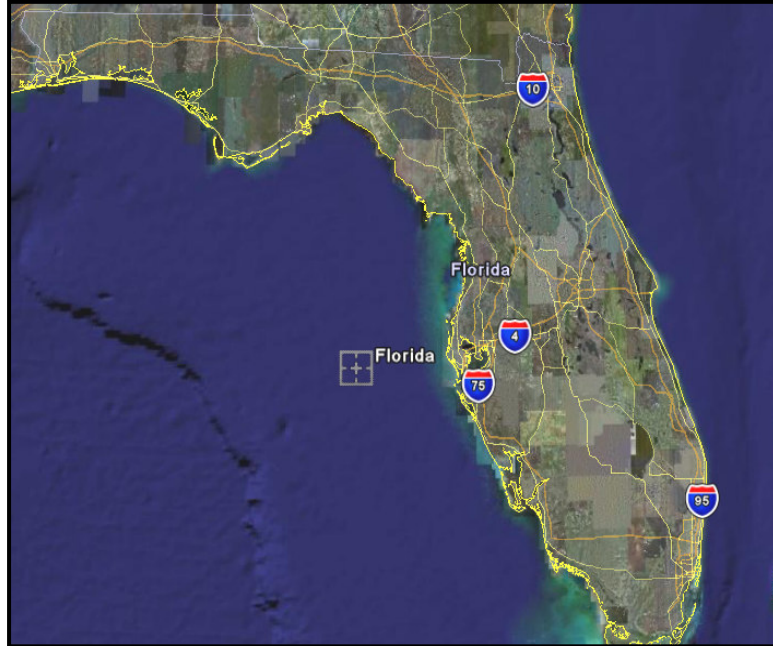
**FIGURE 10. Exit Ramp Segment Lengths for Four Ramp Configurations**

From the four figures, four bold lines added to each one illustrate the study field for exit ramp sections. Even they have special design patterns as they appear, the principles are unique. This is intended to obtain useful results and raise the accuracy of the analysis.

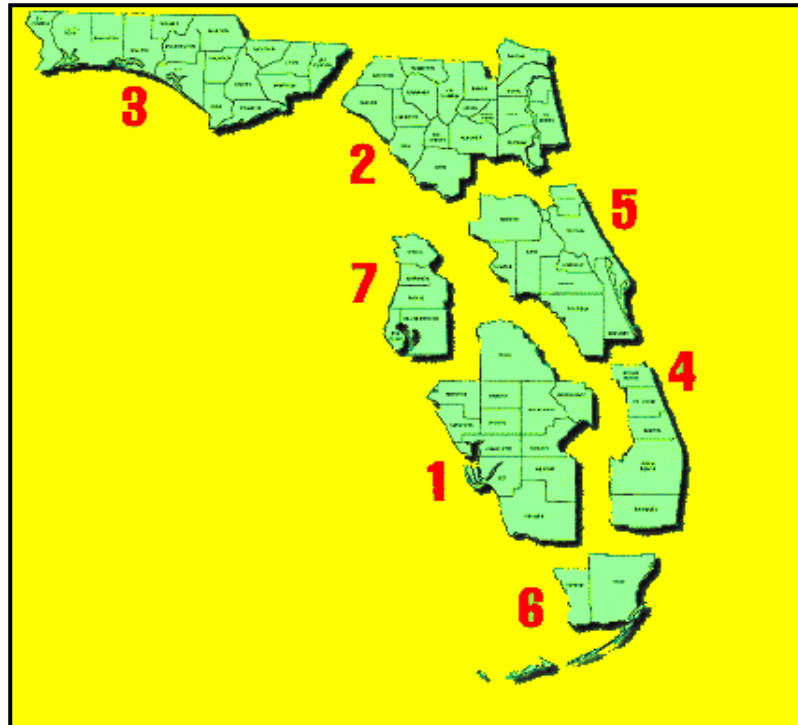
### **4.3 Selected Sites Information**

In this study, crash data were collected at research segments in the State of Florida. After checking the available sites, the site resources are limited. In this reason, all the freeways are examined in order to get reasonable sample sites. Following the sites criteria before, a total of 12 Interstate Highways, 10 expressways, 1 turnpike and 1 parkway are overviewed and sites are collected on these freeways. These freeways provide high service level with high design standards. Figure 11 below lists the most important four interstate highways. Interstate Highway 75 (I-75) and Interstate Highway 95 (I-95) are both north-south directions while Interstate 4 (I-4) and Interstate Highway 10 (I-10) are east-west directions. Other highways connect intra-region or inter-regions as to provide better traffic operations at limited accesses.

Florida divided eight districts for the whole state, from District One to District Eight. District One through District Seven have their local offices to manage each district respectively. District eight is the toll roads that are built, managed and maintained by all Florida areas. FIGURE 12, the District Map, gives an idea about the seven districts allocation in the Florida. The figure is original from FDOT Community Traffic Safety Teams (CTST). These selected freeways are dispensed in all the eight districts and Table 1 lists the detailed information of each district.



**FIGURE 11. Florida Interstate Highway System**



**FIGURE 12. Florida District Map**

**Table 1. FDOT Districts Distributions for Selected Sample Sites**

District Number	Freeways
One	I-75, I-4;
Two	I-295, I-10, I-75, I-95;
Three	I-10, I-110;
Four	I-595, I-75, I-95;
Five	I-4, I-75, I-95, Bee Line Exp, East-West Expressway, Central Florida Greenway Expressway;
Six	I-395, I-75, I-95, I-195, Dolphin Expressway, 826 State Highway, Palmetto Expressway, Florida Turnpike, Don Shula Expressway;
Seven	I-375, I-75, I-275, I-175, I-4, Veterans Expressway, S Crosstown Expressway, N Memorial Expressway;
Eight	Florida Turnpike, Polk Parkway;

### 4.3.1 Freeway Diverge Areas

The task of site collection is the most time-consuming and tedious work in this study. Hundreds of sites are available and each site needs to be checked patiently and reviewed carefully to make sure all the related data are correct. Area photos for each site were pulled together. However, some sites are under reconstructions or have been closed for some time during the study period. Some sites did not have detailed site information such as AADT, especially at some expressways. Since some sites did not have full information, they did not meet the site requirements as mentioned before. These sites might be large curvatures, low posted speed limit as 45 mph, grade variation much higher than the expected one and so on. After reviewing the area photos for freeway diverge areas in the State of Florida, 424 sites were selected for the freeway diverge segments. Among these sites, 220 sites are Type 1 exit ramps-parallel from a tangent single-lane exit; 96 sites are Type 2 exit ramps-single lane exit ramp without a taper; 77 sites are Type 3 exit ramps-two lane exit ramp with an optional lane; and 31 sites are Type 4 exit ramps-two lane exit ramp without an optional lane. Table 2 lists the site resources for each type.

**Table 2. Sites Resource Distributions for Freeway Diverge Areas**

Exit Ramp Type	Total Size	Resource			
		Interstate Highways	Expressways	Turnpikes	Parkways
1	220	220	0	0	0
2	96	96	0	0	0
3	77	59	16	2	0
4	31	17	11	2	1

### **4.3.2 Exit Ramp Segments**

The work of sites gathering on the ramp sections is labor intensive as well. Since the exit ramp sections are sequential to the diverge areas, the sample size basically equals to freeway diverge sites with available data. However several sites did not have ramp ADT because there are no detectors there. These sites are excluded from the exit ramp sites. So a total of 389 sites are determined as the sample size for the entire exit ramp segments.

### **4.4 Site Selection Procedures**

The processes of site selection can be explained in three steps, field study, site information collection, and site review. Field study is the first step to collect raw data as geometric data, site notification data and other related factors. Based on these data, the sites ID could be obtained from Florida road identification systems: Straight-Line Diagram (SLD) and Florida Traffic Information CDs. Finally, all the selected sites are checked again to acquire available sites.

#### **4.4.1 Site Selection Procedure 1**

Step 1 - Field Study: Field study collects site location and geometric conditions which match the requirements and criteria. The photograph maps were obtained from each district traffic information CD. For each site, simple sketches with geometric information were checked to find the following information:

- 1) Major freeway names;
- 2) Freeway directions;

- 3) Ramp types;
- 4) Deceleration lane lengths;
- 5) Number of lanes in freeways;
- 6) Post Speed Limits on freeways;
- 7) Upstream 1500 ft distances measurements from the painted nose;
- 8) Downstream 1000 ft distances measurements from the painted nose;
- 9) Exit ramp directions;
- 10) Ramp lengths;
- 11) Number of lanes in the ramp;
- 12) Ramp suggested or post speed limit;
- 13) Number of lanes changing on the ramp sections;
- 14) Ramp terminal control types;
- 15) Secondary road name;
- 16) Distances from the first upstream intersection on the secondary road;
- 17) Distances from the first downstream intersection on the secondary road;
- 18) Number of lanes on the secondary roads.

#### **4.4.2 Site Selection Procedure 2**

Step 2 - Extracting Road ID: SLD and Florida Traffic Information (FTI) annual CDs were obtained from corresponding FDOT district offices. The road mileposts and road identification numbers for each site were gathered from SLD and ADT each year were subtracted from traffic information CDs. These kinds of information are listed below:



- 19) Section and subsection number of the freeways;
- 20) Section and subsection number of exit ramp sections;
- 21) Milepost on the beginning and end of the segment length for diverge areas;
- 22) Milepost on the beginning and end of the segment length for exit ramps;
- 23) Site number for freeways;
- 24) Site number for exit ramps.

#### **4.4.3 Site Selection Procedure 3**

Step 3 - Site Review: Each site and the related information were checked again to prove that all the data are correct and confirm that no significant reconstruction had taken place at the selected study sites during the study period.

#### **4.5 Section Number, Milepost and Site Identification Number**

The section number and milepost for each selected freeway segment was obtained from the SLD provided by the Florida Department of Transportation. The purpose of using section numbers and mileposts is to consist with FDOT crash database. Each section number contains eight digital codes which were used to identify one specific road. The first two digital codes are the county number for each district. The subsequent three digital numbers are section numbers and the last three digits are the subsection numbers. While looking for a location in a site, section number is not enough. The milepost was additional information to recognize the position on the roadway segment. Mileposts are made from the beginning of a road way from south to north or from west to east. For example, I-75 in Hillsborough County (section number '10' '075' '000') begins at the

Manatee/Hillsborough county line as milepost 0.000 and ends as milepost 36.25 at Pasco/Hillsborough County.

Site ID is another index in the annual FTI CDs which contained several essential parameters including AADT, peak hour factor, and other volume related data. Six numbers are combined. The first two are the county number and the rest four digits are the sites recognized ID. The site ID for I-75 at Bruce B. Down's exits is '10' '0153'. The AADT for this section could be obtained from AADT annual report through site ID.

#### **4.6 Crash Database**

Based on the range in mileposts of each segment, crash data reported was obtained from the crash database maintained by the State of Florida. In 2003, the FDOT renamed all the freeways exit ramps for the whole state. Accordingly, the crash database updated the exit ramp numbers for the entire database. Due to this reason, crash data for freeway exit ramps before 2004 include a lot of missing information and, as a result, cannot be used in this study. A three-year time frame, from 2004 through 2006, was selected to obtain crash data. Eighty-six variables are enclosed in the FDOT crash database including site identification, time of crashes, traffic conditions, geometric conditions, crash detailed information as location, direction, crash type, severity and so on. The software SPSS would be used to examine the crash data. Figure 13 shows the SPSS format from FDOT crash database for one site.

no	date	time	day	district	county	section	subsection	milepost	V10	V11	V direct
1	753523090	2005-11-22	18:00	2	1	1	75	0	8.263	571	.000
2	753549860	2005-10-03	01:25	1	1	1	75	0	8.287	571	.024 MI N
3	753875270	2006-10-23	12:50	1	1	1	75	0	8.287	571	.024 MI N
4	769593310	2006-10-14	16:52	6	1	1	75	0	8.296	571	.036 MI N
5	756662420	2006-02-18	12:35	6	1	1	75	0	8.655	944	.100 MI S
6	751842580	2005-05-14	21:55	6	1	1	75	0	8.697	575	.078 MI S
7	709691280	2005-04-16	01:50	6	1	1	75	0	8.732	575	.043 MI S
8	746067270	2005-08-03	23:34	3	1	1	75	0	8.733	575	.042 MI S
9	746067330	2005-09-06	06:40	2	1	1	75	0	8.733	575	.042 MI S
10	753523480	2006-02-03	19:45	5	1	1	75	0	8.733	575	.042 MI S
11	713693160	2005-06-06	06:36	1	1	1	75	0	8.744	575	.031 MI S
12	751840300	2006-02-03	19:29	5	1	1	75	0	8.744	575	.031 MI S
13	751840310	2006-02-03	19:30	5	1	1	75	0	8.744	575	.031 MI S
14	713509450	2004-06-08	19:45	2	1	1	75	0	8.781	574	.000
15	753514610	2005-07-12	16:15	2	1	1	75	0	11.469	946	.031 MI N
16	769574770	2006-05-21	19:04	7	1	1	75	0	11.559	583	.006 MI N
17	753513170	2005-08-13	10:54	6	1	1	75	0	14.842	593	.047 MI N
18	709755250	2004-03-12	17:34	5	1	1	75	0	14.842	593	.047 MI N
19	769562550	2006-10-07	19:50	6	1	1	75	0	14.891	593	.096 MI N
20	769532270	2006-08-19	16:57	6	1	1	75	0	14.903	593	.108 MI N
21	753872280	2005-03-09	00:00	3	1	1	75	0	20.921	610	.120 MI N
22	756652830	2006-02-24	08:12	5	1	1	75	0	20.541	611	.256 MI S

Figure 13. SPSS Example format from FDOT crash database

#### 4.7 Combination of Crash Data with Site Information

Each site has a specific database consisted of geometric variables, traffic data and relative crash information. The Excel file will be used to arrange the format of each location for useful variables. The following Figure 14 shows part data from the combining database for some sites.

A	B	C	D	E	F	G	H	I	J	K
1	Exit name	Ramp type	Ramp Configurations	Mainline Dist	SECTION NUMBER	Secondary name	Direction	PAINT NOS	sub-section	
2	1-75 EXIT 158-1	1	Diamond	1-75	01-075-000	Trucks Grade	S--N	8.259		301
3	2-75 EXIT 158-2	1	Diamond	1-75	01-075-000	Trucks Grade	N--S	8.775		304
4	3-75 EXIT 161-1	1	Diamond	1-75	01-075-000	Jones Loop Rd	SE--NW	11.544		307
5	4-75 EXIT 161-2	1	Diamond	1-75	01-075-000	Jones Loop Rd	NW--SE	12.073		310
6	5-75 EXIT 164-1	1	Diamond	1-75	01-075-000	Federal 17	S--N	14.788		311
7	6-75 EXIT 167-2	1	Diamond	1-75	01-075-000	Harbor View Rd	NW--SE	18.168		318
8	7-75 EXIT 170-1	1	Diamond	1-75	01-075-000	Kings Hwy	S--N	20.797		319
9	8-75 EXIT 170-2	1	Diamond	1-75	01-075-000	Kings Hwy	N--S	21.342		322
10	9-75 EXIT 101-1	1	Diamond	1-75	03-175-000	Collier Blvd	E--W	50.107		1
11	10-75 EXIT 123-1	1	Diamond	1-75	12-075-000	Corkscrew Rd	S--N	8.095		5
12	11-75 EXIT 123-2	1	Diamond	1-75	12-075-000	Corkscrew Rd	N--S	8.681		8
13	12-75 EXIT 128-1	1	Outer Connection	1-75	12-075-000	Alico Rd	S--N	12.23		9
14	13-75 EXIT 138-1	1	Diamond	1-75	12-075-000	Dr Martin Luther King	S--N	22.352		23
15	14-75 EXIT 138-2	1	Diamond	1-75	12-075-000	Dr Martin Luther King	N--S	22.907		26
16	15-75 EXIT 139-1	1	Diamond	1-75	12-075-000	Luckett Rd	S--N	23.894		27
17	16-75 EXIT 139-2	1	Diamond	1-75	12-075-000	Luckett Rd	N--S	24.39		30
18	17-75 EXIT 141-1	1	Diamond	1-75	12-075-000	Palm Beach Blvd(80)	S--N	25.809		31
19	18-75 EXIT 141-2	1	Diamond	1-75	12-075-000	Palm Beach Blvd(80)	N--S	26.307		34
20	19-75 EXIT 143-2	1	Diamond	1-75	12-075-000	Bayside Rd	N--S	28.658		38
21	20-75 EXIT 217-1	1	Outer Connection	1-75	13-075-000	State 70	S--N	3.409		3
22	21-75 EXIT 217-2	1	Outer Connection	1-75	13-075-000	State 70	N--S	3.997		8
23	22-75 EXIT 220-1	1	Parclo Loop	1-75	13-075-000	State 84	S--N	6.993		9
24	23-75 EXIT 220-2	1	Outer Connection	1-75	13-075-000	State 84	N--S	7.599		14
25	24-75 EXIT 224-2	1	Outer Connection	1-75	13-075-000	Federal 301	NW--SE	11.287		18
26	25-75 EXIT 229-1	1	Diamond	1-75	13-075-000	Moccasin Wallow Rd	SW--NE	15.85		19
27	26-75 EXIT 229-2	1	Diamond	1-75	13-075-000	Moccasin Wallow Rd	NE--SW	16.455		22
28	27-4 EXIT 31-1	1	Diamond	1-4	16-320-000	Kathleen Road	SW--NE	4.86		60
29	28-4 EXIT 31-2	1	Diamond	1-4	16-320-000	Kathleen Road	NE--SW	5.373		62
30	29-4 EXIT 33-1	1	Diamond	1-4	16-320-000	Lakeland Hills Blvd (3)	SW--NE	8.468		82
31	30-4 EXIT 38-1	1	Diamond	1-4	16-320-000	33 State Road	SW--NE	12.132		90

FIGURE 14. Example of Combining Database

## **CHAPTER FIVE**

### **DATA ANALYSIS**

Detailed procedures and results of crash data analyses were performed in this chapter. As mentioned before, freeway diverge areas and entire exit ramp sections are two separate research subjects in the study. Quantitative investigations were conducted to find out crash characteristics and the contributing factors in order to evaluate safety performances both on the freeway diverge areas and exit ramp sections.

#### **5.1 Outline of Data Analysis**

Crash data for freeway diverge areas and exit ramps are analyzed independently as to evaluate the safety performances on the two research sections in this study. As mentioned previously, the cross-sectional comparisons were conducted to compare the effects of the four exit ramp types on the safety performance of freeway diverge areas and effects of ramp configurations on the safety performance of the exit ramp sections respectively. On the freeway diverge areas, a total of 424 sample sites were collected. The sample size was divided into four groups according to the four different exit ramp types as mentioned before. Group 1 has 220 sites for Type 1 exit ramps, Group 2 has 96 sites for Type 2 exit ramps, Group 3 has 77 sites for Type 3 exit ramps and Group 4 has 31 sites for Type 4 exit ramps. On the exit ramp sections, a total of 389 sites with 247

sites for diamond ramps, 93 sites for out collection ramps, 26 sites for free-flow loop ramps, and 23 sites for parco loop ramps were categorized. Two crash predictive models were developed for the two research subjects to find the contributing factors to the crashes occurring at diverge areas and exit ramp sections.

First, average crash frequency and crash rate for each group on the two research subjects were calculated. Statistical tests were conducted to compare each section at a 90% confidence level one by one. Second, each group had the sample sites classified by target crash types that have three most crash frequencies among all the crash types. Then the average crash number and crash rates by target crash types were calculated by using crash data from 2004 to 2006 and the corresponding statistical tests were performed. Third, crash severity categories such as PDO (property-damage-only), injury and fatality were compared with corresponding average crash number and crash rate by each ramp configuration. The comparisons were followed by statistical significance tests at 90% confidence level which is believable and commonly used in crash analysis. Finally, two predict models were built to find the predictive crash number under some definite conditions according to the independent variables.

## **5.2 Freeway Diverge Areas**

### **5.2.1 Comparison of Average Crash Frequency and Crash Rate**

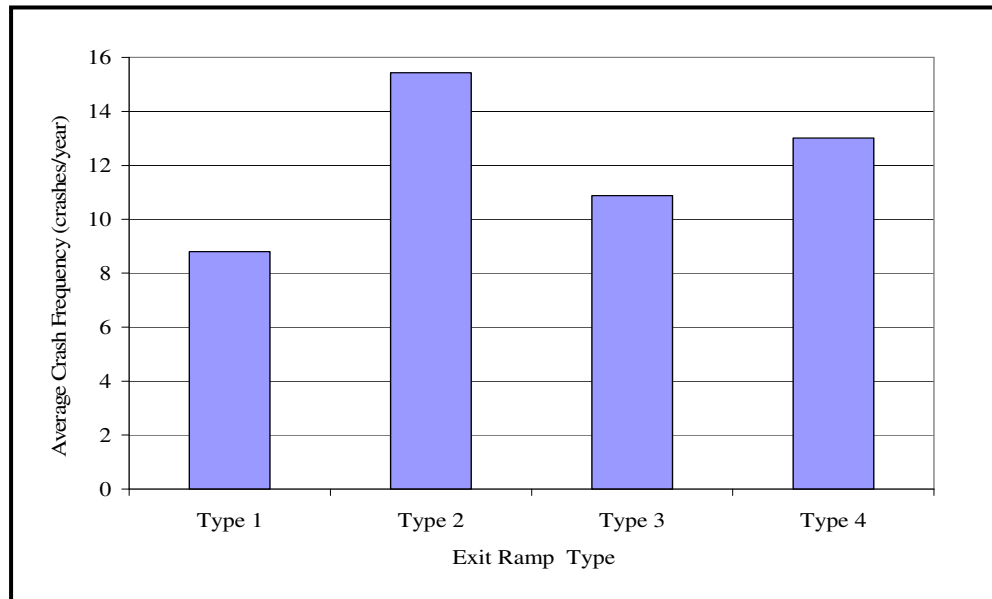
A total of 13968 crashes were reported at selected freeway diverge segments for three years from 2004 to 2006. The crash frequency at selected sites varies from 0 to 60 with a mean of 11.01 crashes per year. Summary statistical analyses of crash frequency and crash rate for four exit ramp groups were illustrated in Table 3. The average crash

frequency and crash rate for different exit ramp groups were compared in Figure 15 and 16. Average crash frequency is the mean value of all the crashes in one group each year. In this study, crash rate is defined in the methodology chapter, set as crashes per million vehicles per mile. The average daily traffic for each site was collected and the segment length was identified equally for each site. For example, if site I has 10 crashes for the three years from 2004 to 2006, segment length is 0.47 miles (2500 ft), and the ADT is 10,000 vehicles per day, the crash rate for this site I could be calculated as following:

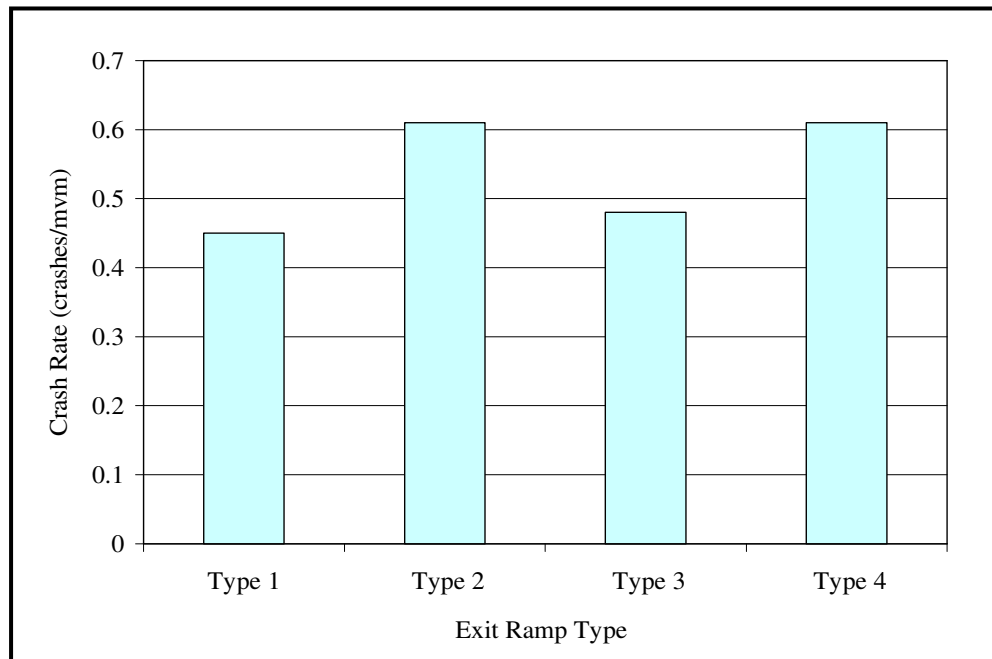
$$\text{Crash Rate for the Site I} = \frac{1,000,000 \times 10 \text{ crashes}}{365 \text{ days} \times 3 \text{ years} \times 10,000 \text{ vpd} \times 0.47 \text{ miles}} = 1.94$$

The average crash rate for a particular group is calculated by the mean value of crash rates for all sites. As shown in Figure 15 and 16, the type 1 exit ramp group has the best safety performance in terms of the lowest average crash frequency and crash rate comparing to other exit ramp types. The figures also show that the type 2 exit ramp group has the highest average crash frequency and crash rate. The trends of average crash frequency and crash rate among the four types showing in the figures are sequent. Type 1 and Type 2 have the lowest and highest average crash frequency and crash rate among the 4 groups while the average crash frequency and crash rate for Type 3 and Type 4 is a little higher than Type 1 and a little lower than Type 2. Table 3 listed the detailed analysis such as mean, median, max and min values for each group. On average, the sites in type 2 exit ramps group report the most average crash frequency as 15.4 crashes per year in freeway diverge segments. As compared those in Type 1 exit ramp group, sites in Type 2 exit ramp group reports 75% more crashes per year for one lane exit ramp. The average crash rate at sites with Type 2 is also 35.6% higher when comparing those with Type 1

per year. For two lane exits, Type 3 appears 20% and 14% less average crash frequency and crash rate than Type 4.



**Figure 15. Comparison of Average Crash Frequency among Four Exit Ramp Types**



**Figure 16. Comparison of average Crash Rate among Four Exit Ramp Types**

**Table 3. Summary of Average Crash Frequency and Crash Rate for  
Four Exit Ramp Types**

Type	Crash Frequency (No. of crashes per year)				Crash Rate (No. of crashes per million vehicles per mile)			
	1	2	3	4	1	2	3	4
No. of Sites	220	96	77	31	220	96	77	31
Total No. of Crashes per year	1934	1481	824	417	1934	1481	824	417
Average No. of Crashes	8.8	15.4	10.7	13.45	0.45	0.61	0.48	0.61
St. Deviation	6.23	13.8	8.14	11.3	0.36	0.45	0.32	0.37
Median	4.7	13.2	8.67	12.3	0.36	0.48	0.42	0.55
Max	54	30	31	60	1.36	1.98	1.18	1.24
Min	0	0	1	0	0	0	0.061	0

The site with the highest crash frequency is located on Interstate Highway 95 (I-95) in District 4 along the southbound. Figure 17 below showed the site picture. During the three-year time period, 179 crashes were reported at selected freeway segments. 101 are injury plus fatal crashes and the others are PDO crashes. Field observation was made to the particular site to identify the undesirable driving behaviors contributing to the high crash frequency. The segment is located on a five-lane freeway with a posted speed limit of 55 mph. The exit ramp is found to be a type 4 exit ramp which is a two-lane exit ramp without an optional lane. The annual daily traffic volume (ADT) on the freeway is 224,000 vehicles per day. The reasons that had most crashes might be the traffic volume



was higher than usual, and the exit ramp type in the site caused more weaving maneuvers in diverge areas. Drivers who mistakenly entered the exit lane need to merge back into through lanes to continue on the freeway; while vehicles exiting freeways may need to change up to four lanes to weave to the outer exit lane. Some severe weaving conflicts have been observed at the site that indicates a high potential crash prone area.



**FIGURE 17. Site Picture for I-95 Southbound Exit 74**

In order to compare whether the average crash frequencies and crash rates for the four exit ramp types have significant different from each other, hypothesis tests were applied to evaluate the samples. For example, the statistical Z test to compare the average crash frequency for Type 1 exit ramp and Type 2 exit ramp was performed as following:

- 1) The mean values for two populations Type 1 exit ramp and Type 2 exit ramp are  $\mu_1$  and  $\mu_2$ ;
- 2) Mean value and standard deviation of the two samples for Type 1 exit ramp are 8.8 and 6.73 respectively, while those for Type 2 exit ramp are 15.4 and 13.8;

- 3) The sample numbers for Type 1 exit ramp and Type 2 exit ramp are 220 and 96 accordingly;
- 4) The null hypothesis is  $H_0: \mu_1 = \mu_2$ , the alternative hypothesis is  $H_a: \mu_1 \neq \mu_2$ ;
- 5) Assuming the difference in the sample means of the two population fit the normal distribution and 90% confidence level was chosen for this study;
- 6) 
$$Z_0 = \frac{|8.8 - 15.4|}{\sqrt{\frac{6.23^2}{220} + \frac{13.8^2}{96}}} = 3.06 ;$$
- 7) The critical value for  $Z_{\alpha/2}$  is 1.645 which is smaller than 3.06 so that the null hypothesis is rejected;
- 8) The conclusion could be get as the average crash number for Type 1 and Type 2 exit ramp is significant different at a 90% confidence level.

The average crash frequency and crash rate for each population were tested at a 90% confidence level. Table 4 listed all the results for the hypothesis tests. The comparison of the average number of crashes for Type 1 and Type 2 exit ramp showing “1:2” is significantly different at a 90% confidence level meaning “YES” in the table. For average crash frequency, Type 1 shows significant different from the other three types while Type 2 has significantly different average crash frequency with Type 3 but not with Type 4 exit ramps. The results were consistent for average crash frequency and crash rate except comparing Type 1 and Type 3 exit ramps. This might be the cause that crash rate has limited the traffic volume impacts. For one lane exit ramp, Type 1 exit ramp is much safer than Type 2 exit ramp. For two-lane exit ramp, Type 3 group did appear significant difference with Type 4 exit ramp on average crash rate.

**Table 4. Summary Hypotheses Tests of Average Crash Frequency and Crash Rate for Four Exit Ramp Types**

Crash	Statistics Results for Two Mean Tests: 90%					
	1:2	1:3	1:4	2:3	2:4	3:4
Frequency	YES	YES	YES	YES	NO	NO
Rate	YES	NO	YES	YES	NO	YES

### 5.2.2 Comparison of Target Crash Type

Three target crash types as mentioned before, rear-end crashes, angle crashes and sideswipe crashes, were compared for each exit ramp type to find the crash characteristics among the four ramp types. Table 5 lists the total numbers of crashes, percentages of total crashes, average crash numbers, standard deviations and median values for the four ramp types by three target crash types. The average crash numbers for rear-end crashes and sideswipe crashes among the four types have larger differences among each other while those for angle crashes have minor distinctions among the four ramp types. In Table 6, the average crash rate for Type 1 and Type 3 equal of 0.21 crashes per million vehicles per mile per year for rear-end crashes. But Type 2 and Type 4 have 30% and 34.4% more crashes than these two types.

Figure 18 illustrates that the percentage of rear-end crashes for 4 types are 45.97%, 48.41%, 41.26%, and 44.60%. Type 3 group counts less percentage than the other three groups. It is reasonable that two-lane exit ramp with an operational lane will provide more spaces for vehicles acceding or decreasing speed in the diverge area than single-

lane exit ramp. With the optional lane, some unfamiliar drivers or these drivers on the wrong lanes would have an opportunity to either continue or leave the freeway mainline segments. The sideswipe crashes is the crash type that have the second largest crash number. Table 5 shows the percentage of each group for sideswipe crashes is 15.82%, 15.67%, 15.05% and 16.31%. That might be a result of the additional weaving maneuvers for Type 4 comparing to Type 3. As Type 4 exit ramp group, some drivers are willing to continue on the freeways when they may misunderstand the inner lane of two exits as a through lane. When they found it was an exit lane, they might take some dangerous maneuvers such as quickly reducing speed, immediately changing lanes, or even completely stopping which often cause more sideswipe crashes happening to continue driving on freeways. Type 3 appears less rear-end and sideswipe crashes than other three exit ramp types.

**Table 5. Summary of Average Crashes Numbers by Target Crash Types for Four Exit Ramp Types**

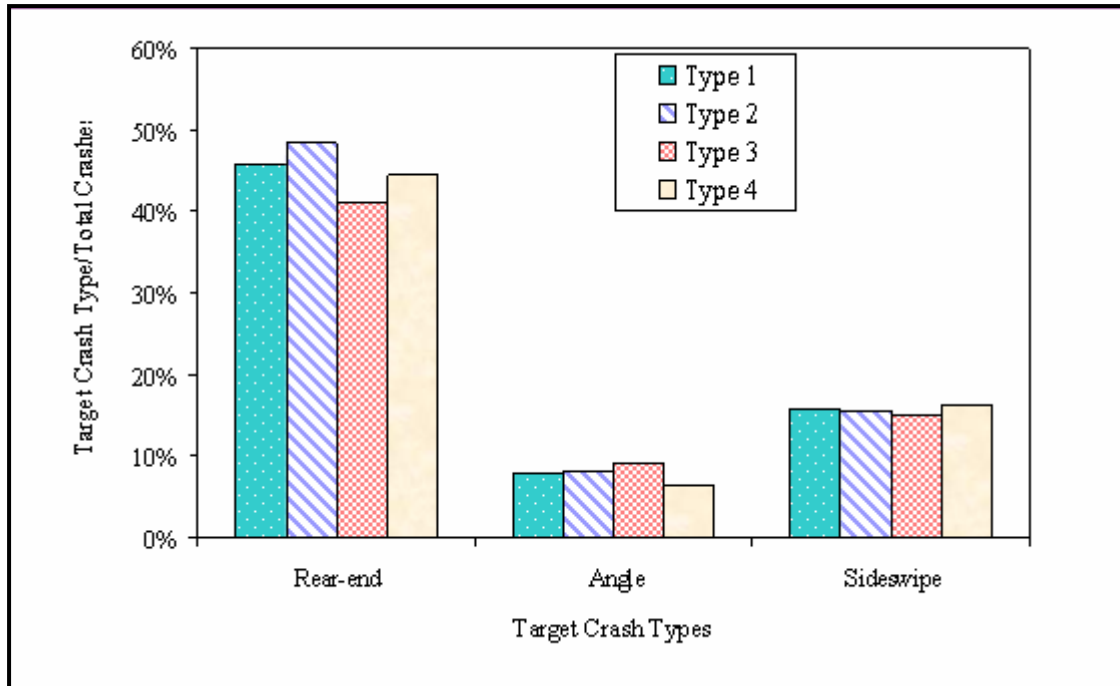
Target Crash Types	Statistics	Type 1	Type 2	Type 3	Type 4
Rear-end Crashes	No. of Crashes per year	899	717	340	186
	(% of Total)	(45.97%)	(48.41%)	(41.26%)	(44.60%)
	Average No. of Crashes	4.09	8.06	4.42	6.00
	Standard Deviation	7.50	8.75	4.40	7.05
	Median	2	6	3	6

**Table 5 (continued)**

Angle Crashes	No. of Crashes per year (% of Total)	152 (7.88%)	121 (8.19%)	76 (9.22%)	27 (6.47%)
	Average No. of Crashes	0.69	1.26	0.99	0.87
	Standard Deviation	0.91	1.16	0.79	0.89
	Median	0.67	1.33	1	1
Sideswipe Crashes	No. of Crashes per year (% of Total)	306 (15.82%)	232 (15.67%)	124 (15.05%)	68 (16.31%)
	Average No. of Crashes	1.39	2.42	1.61	2.19
	Standard Deviation	3.52	2.10	1.43	1.97
	Median	1	2.33	1.33	2.67

**Table 6. Summary of Average Crashes Rates by Target Crash Types for  
Four Exit Ramp Types**

Target Crash Type	Statistics	Type 1	Type 2	Type 3	Type 4
Rear-end Crashes	Average No. of Crashes	0.210	0.300	0.210	0.320
	Standard Deviation	0.250	0.291	0.225	0.350
	Median	0.120	0.170	0.260	0.130
Angle Crashes	Average No. of Crashes	0.054	0.054	0.050	0.053
	Standard Deviation	0.100	0.028	0.029	0.032
	Median	0.040	0.050	0.055	0.050
Sideswipe Crashes	Average No. of Crashes	0.091	0.115	0.118	0.098
	Standard Deviation	0.118	0.111	0.067	0.054
	Median	0.060	0.090	0.120	0.060



**Figure 18. Comparison of Percentages by Target Crash Types for Four Exit Ramp Types**

Proportionality tests were then conducted to compare the percentages of difference among the four groups. The procedures of proportionality test are similar to Z tests mentioned before. For example, the portions of rear-ends crashes to total crashes for Type 1 exit ramps and Type 2 exit ramps were tested as following:

- 1) The two populations, Type 1 exit ramp and Type 2 exit ramp, have the percentages of rear-end crashes to the total crashes as  $p_1$  and  $p_2$ ;
- 2) The percentages of rear-end crashes to the total crashes for the two samples of Type 1 exit ramp and Type 2 exit ramp are  $\hat{p}_1$ , 45.97%, and  $\hat{p}_2$ , 48.41%;
- 3) Type 1 exit ramp has 220 sites and Type 2 exit ramp has 96 sites;

- 4) The null hypothesis is  $H_0: p_1 - p_2 = 0$ , the alternative hypothesis is  $H_a: p_1 - p_2 \neq 0$ ;
- 5) Assuming the difference of proportions for rear-end crashes in the two samples fits the normal distribution and 90% confidence level was chosen for this study;
- 6) 
$$Z^* = \frac{|45.97 - 48.41|}{\sqrt{\frac{45.97(100 - 45.97)}{220} + \frac{48.41(100 - 48.41)}{96}}} = 0.40$$
;
- 7) The critical value for  $Z_{\alpha/2}$  is 1.645 which is much larger than  $Z^*$  so that the null hypothesis can not be rejected;
- 8) The conclusion is that the proportions of rear-end crashes for Type 1 and Type 2 exit ramp is not significantly different at 90% confidence level;

All the results are given in Table 7. The results of the proportionality tests show that the percentages of both rear-end and angle/right-turn crashes among the four exit ramp groups on the freeway diverge areas did not have statistically significant differences with 90% level of confidence. This conclusion indicated that the three crash types having the highest crashes did not differ a lot for the four types.

**Table 7. Z Statistics for Proportionality Tests by Target Crash Types for Four Exit Ramp Types**

Crash Type	Proportionality Tests:90%					
	1:2	1:3	1:4	2:3	2:4	3:4
Rear-end	NO	NO	NO	NO	NO	NO
Angle	NO	NO	NO	NO	NO	NO
Sideswipe	NO	NO	NO	NO	NO	NO

### 5.2.3 Comparison of Crash Severity

Among the total crashes reported for selected freeway segments, 7518 property damage only (PDO) crashes, 6333 injury crashes and 117 fatal crashes were included. In this study, crash severity was compared among different exit ramp groups by comparing percentages of PDO crashes and injury plus fatal crashes. Summary statistics for crash severity for different exit ramp groups are given in Table 8 and 9 and compared in Figure 19. For one lane exit ramp, Type 1 exit ramp has less average crash frequency and crash rate for both PDO crashes and injury plus fatality crashes than the type 2 exit ramp group. Also, Type 3 exit ramp appears less average crash frequency and average crash rate for the two crash severity categories for two-lane exit ramps. As compared in Figure 19, the percentage of injury plus fatality crashes does not significantly differ from each other among different exit ramp groups. Type 2 exit ramp has slightly higher percentage of injury plus fatality crashes comparing to Type 1 exit ramp for one lane exit ramp and Type 4 exit ramp is a bit higher than Type 3 exit ramp for that as well.

**Table 8. Summary of Average Crash Number by Crash Severity for Four Exit Ramp Types**

Crash Severity	Statistics	Type 1	Type 2	Type 3	Type 4
PDO	No. of Crashes (% of Total)	1072 (55.43%)	771 (52.06%)	444 (53.88%)	219 (52.52%)
	Average No. Of Crashes	4.87	8.03	5.77	5.23
	Standard Deviation	6.92	7.64	4.82	6.57
	Median	3.67	13.80	4.67	9.00

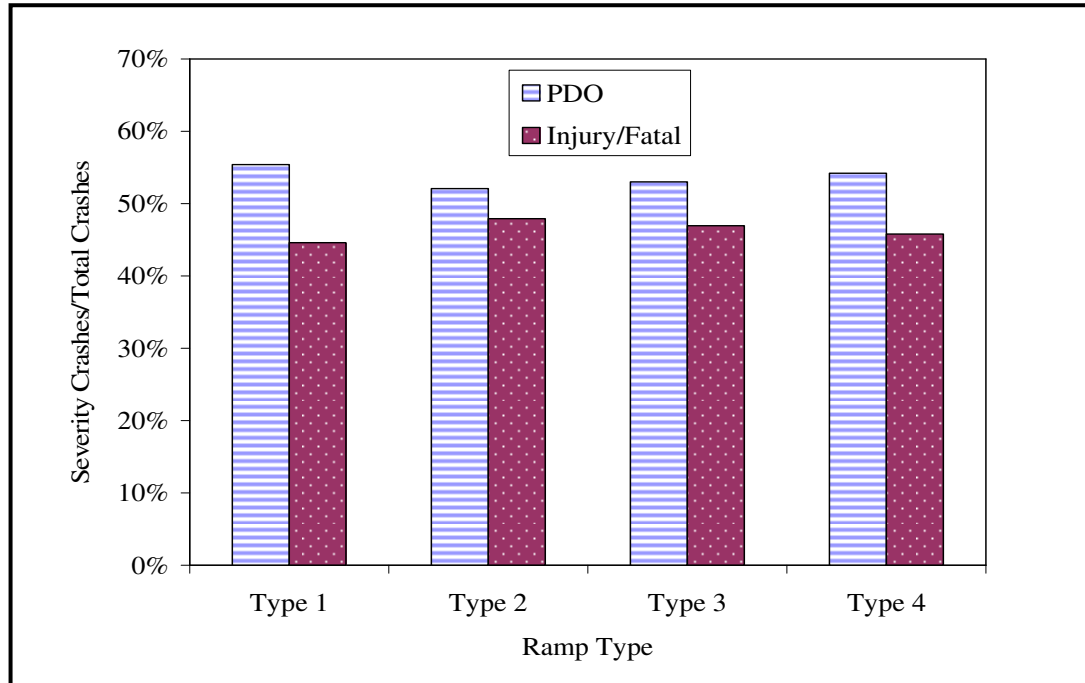


**Table 8. (Continued)**

Injury/ Fatality Crashes	No. of Crashes (% of Total)	862 (44.57%)	710 (47.94%)	380 (46.12%)	198 (47.48%)
	Average No. Of Crashes	3.92	7.40	4.94	6.39
	Standard Deviation	5.38	7.18	4.16	5.18
	Median	2.33	6	3.33	4.67

**Table 9. Summary of Average Crash Rates by Crash Severity for  
Four Exit Ramp Types**

Crash Severity	Statistics	Type 1	Type 2	Type 3	Type 4
PDO	Average No. of Crashes	0.325	0.342	0.276	0.356
	Standard Deviation	0.292	0.314	0.204	0.231
	Median	0.205	0.245	0.24	0.32
Injury/ Fatality Crashes	Average No. of Crashes	0.204	0.287	0.238	0.278
	Standard Deviation	0.155	0.2	0.167	0.174
	Median	0.17	0.23	0.18	0.28



**FIGURE 18. Comparison of Percentages by Crash Severity for Four Exit Ramp Types**

Proportionality tests were also conducted for testing the differences in crash severity among four exit ramp groups. The crash database includes 6420 injury plus fatality crashes for three years time frame. The null hypothesis of the proportionality test is that the percentages of injury plus fatal crashes in different exit ramp groups are equal. The conclusions of Z statistics for the proportionality tests are listed in Table 10. The calculating procedures are same as target crash types mentioned above. Based on the Z statistic tests, there is no evidence to reject the null hypothesis with 90% level of confidence. The results suggest that, even the exit ramp types significantly impacts the average crash frequency and average crash rate, the differences of their impacts on crash severity are not statistically significant.

**Table 10. Z Statistics of Proportionality Tests by Crash Severity for  
Four Exit Ramp Types**

Crash Severity	Z Statistics for Proportionality Tests					
	1:2	1:3	1:4	2:3	2:4	3:4
PDO	NO	NO	NO	NO	NO	NO
Injury/Fatal	NO	NO	NO	NO	NO	NO

#### **5.2.4 Crash Predictive Model**

In this study, a crash prediction model was developed to identify the factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of different types of freeway exit ramps. Considering the available data source, a total of 404 observation sites were used in the model. Since some sites did not have ramp ADT and ramp design speeds. The variables were believed significantly important to have potential crashes. The dependent variable of the model is the average crash frequency per year reported at selected freeway diverge areas. Seventeen independent variables were initially considered when building the crash prediction model. The four exit ramp types were defined as three indicator variables. The initially selected independent variables are described in Table 11. The value of each variable are also listed in the table.

**Table 11. Description of Initially Considered Independent Variables  
on Freeway Diverge Areas**

Independent Variable	Value	Frequency
Type 2 exit ramp	1 Type 2 exit ramp 0 Otherwise	92
Type 3 exit ramp	1 Type 3 exit ramp 0 Otherwise	75
Type 4 exit ramp	1 Type 4 exit ramp 0 Otherwise	22
Number of lanes on mainline	1 One lane on mainline 2 Two lanes on mainline 3 Three lanes on mainline ..... n N lanes on mainline	404
Number of lanes on exit ramps	1 One lane on mainline 2 Two lanes on mainline 3 Three lanes on mainline ..... n N lanes on mainline	404
Length of deceleration lanes	Distance of the deceleration lanes (mi)	404
Length of entire exit ramps	Distance for the entire ramp from the painted nose to the end of ramp (mi)	404
ADT per year in thousand on freeway sections	Average ADT in thousands for three years 2004~2006	404
ADT per year in thousand on exit ramp sections	Average ADT in thousands for three years 2004~2006	404
Speed difference between mainline and exit ramp	Maximal speed limit difference (mi/h)	404
Road surface condition	0 Dry 1 Wet	404
Land type	0 Primarily business 1 Primarily residential	404

**Table 11 (continued)**

Road surface type	0 Blacktop 1 Concrete	404
Right shoulder type	0 Paved 1 Unpaved	404
Right shoulder width	Width for the right shoulder (ft)	404
Post speed on mainline	Maximal speed limit (mi/h)	404
Post or suggested speed on ramp	Maximal speed limit (mi/h)	404

The crash modeling starts from a Poisson model. For an adequate model, the scaled deviance and Pearson's  $\chi^2$  divided by the degrees of freedom shall be close to one. These two values are used to detect overdispersion or underdispersion in the Poisson regression model. Values greater than 1 indicate overdispersion, while values smaller than 1 indicate underdispersion. In this study, the Pearson's  $\chi^2$  divided by the degrees of freedom was found to be 10.50, indicating the fact that the crash data are overdispersed and NB models shall be used. Stepwise regression method was used to select independent variables in the model. Seven variables were not found to be statistically significant. As a result, these variables were not included into the model. The best model contains ten independent variables. The regression results of the best model are given in Table 12. As shown in the table 12, the scaled deviance and Pearson's  $\chi^2$  divided by the degrees of freedom are 1.12 and 1.27 which are reasonably close to one, indicating the fact that the model is adequately fitted. The final equation of the model is given as follows:

$$Y = \exp(3.1523 + 0.1416X_1 + 0.1354X_2 + 0.2244X_3 + 0.1302X_4 + 1.3470X_5 - 0.9385X_6 + 0.0679X_7 + 0.0223X_8 + 0.0614X_9 - 0.0301X_{10}) \quad (22)$$

Where, Y = expected average crash frequency in a freeway diverge area (crashes/year),

$X_1$  = 1 if the site has a Type 2 exit ramp, 0 others;

$X_2$  = 1 if the site has a Type 3 exit ramp, 0 others;

$X_3$  = 1 if the site has Type 4 exit ramp, 0 others;

$X_4$  = Number of lanes on the mainline sections;

$X_5$  = Length of the deceleration lanes (mile);

$X_6$  = Length of the entire exit ramp (mile);

$X_7$  = ADT per year in thousands on mainline sections;

$X_8$  = ADT per year in thousands on exit ramp sections;

$X_9$  = Speed difference between the post speed limit on mainline and exit ramp sections (mph);

$X_{10}$  = Post speed limit on mainline sections (mph);

**Table 12. Regression Results for Crash Prediction Model for Diverge Areas**

Criteria for Goodness of Fit			
Criteria	DF	Value	Value/DF
Deviance	393	441.5189	1.12
Scaled Deviance	393	441.5189	1.12
Pearson Chi-Square	393	501.1979	1.27
Scaled Pearson	393	501.1979	1.27
Log Likelihood	38746.0924		

**Table 12 (continued)**

Analysis of Parameter				
Parameter	Coefficient	Standard error	$\chi^2$	Pr > $\chi^2$
Intercept	3.1523	0.4205	132.12	<0.0001
Type 2 exit ramp	0.1416	0.1066	0.19	0.0610
Type 3 exit ramp	0.1345	0.1239	0.38	0.0536
Type 4 exit ramp	0.2240	0.1033	0.80	0.0543
Number of lanes on mainline	0.1302	0.0512	4.41	0.1002
Length of deceleration lanes	1.3470	1.2667	1.02	<0.0001
Length of entire ramp	-0.9385	0.1616	35.46	<0.0001
ADT in thousands on mainline	0.0679	0.0079	73.66	<0.0001
ADT in thousands on ramp	0.0223	0.0049	21.00	<0.0001
Speed difference	0.0614	0.0023	69.68	<0.0001
Post speed limit on mainline	-0.0301	0.0188	12.56	0.0129
Dispersion	0.4365	0.0339		

All selected independent variables were statistically significant with 90% confidence level. The coefficients of the model show that the crash counts at freeway diverge areas increase with the mainline lane number, the deceleration lane length, mainline ADT, ramp ADT and post speed limit difference between mainline sections and ramp sections, however decrease with the entire ramp length, and post speed limit on mainline. With the more numbers of lanes on the freeway segments, the potential conflict

points will increase so that the chances occurring crashes increase. ADT both on freeway mainline areas and exit ramp sections would increase the opportunities occurring crashes. It is consistent with previous studies (1, 3). Another two positive variables are the deceleration lengths on diverge areas and the post speed limit differences. It was long believed that crash number would decrease if longer deceleration lengths were applied. However, recently a study presented in last International Symposium on Highway Geometric Design indicated the hypothesis is not correct. The study also proved that longer deceleration length might increase the number of weaving maneuvers and cause more potential crashes than short distances. Speed differences between mainline sections and exit ramp sections have positive influences on the crashes as well. It is intuitive as the larger variations on posted speed, more difficult for vehicles to control operating speeds. Some vehicles might lose controls as hard driving maneuvers.

From the model, it points out fewer crashes with longer exit ramp length. It make sense that longer ramp length would diminish the impacts of exit ramps on the freeway diverge areas. The coefficient for the posted speed limit is negative, implying that crash counts increase with the increase of the posted speed limit of the freeway. This result is a little bit counter-intuitive. A possible explanation is that the variable posted speed limit is correlated with other variables which were not included into the model. For example, it is very possible that a freeway with higher posted speed limit is also designed according to higher standards. Thus, higher posted speeds may also imply wider lane width, better lighting conditions, better signing or pavement marking; and these missing variables could reduce crash freeway at freeway diverge areas.



The coefficients for the three indicator variables are all positive, indicating the fact that the site with the type 1 exit ramp has the least numbers of crashes. This conclusion is consistent with the result of our cross-sectional comparison. The coefficients of the model can be used to quantify the safety impacts of different types of freeway exit ramps. Based on the model, replacing a type 1 exit ramp with a type 2 exit ramp will increase crash counts at freeway diverge areas by  $\exp(0.1416-0)-1=15.57\%$ . Replacing a type 3 ramp with a type 4 ramp will increase crash counts at freeway diverge areas by  $\exp(0.2244-0.1354)-1=10.80\%$ .

## **5.3 Exit Ramp Section**

### **5.3.1 Crash Characteristics**

Four different exit ramp configurations were grouped for each category to evaluate the impacts on the safety performance. A total of 2520 crashes were stated for the entire segments for three years from 2004 to 2006. The sites were grouped for four configurations simply named as D (Diamond), O (Out-connector), F (Free-flow Loop) and P (Parclo Loop). The group D has 247 sites, the group O has 93 sites, the group F has 26 sites and the group P has 23 sites. The average crash frequencies for the four groups are 2.20, 2.32, 2.21 and 1.00 crashes per site per year. Summary statistics for average crash frequency and average crash rate by four exit ramp configuration groups were given in Table 13.

Average crash frequency is the mean value of all the crash frequencies in one group for each year. Crash rate is defined in the methodology chapter as crashes per million vehicles per mile. The volume for each site was collected and segment length was

set as the whole ramp length for the site. The procedures of calculating each exit ramp site were similar to the diverge areas. For example, if site II has 5 crashes for the three years from 2004 to 2006, the entire ramp length is 0.25 miles (1320 ft), and the ADT is 5,000, the crash rate for this site II could be calculated as following:

$$\text{Crash Rate for the Site II} = \frac{1,000,000 \times 5 \text{ crashes}}{365 \text{ days} \times 3 \text{ years} \times 5,000 \text{ vpd} \times 0.25 \text{ miles}} = 3.65$$

The average crash rate for a ramp configuration group is calculated by the mean value of crash rate for all sites. In Table 13, the average crash frequencies indicate the parclo loop group has the less average crash frequency, however the average crash rates point out that the out connection group has the best safety performance while considering the ramp volume and ramp length. The average crash rate is more reliable as it eliminates the impacts of different ramp volumes and ramp distances. The free-flow loop group has more potential crashes in terms of the maximum average crash rate comparing to the other three exit ramp types. The average crash rate for the free-flow loop group is almost 162%, and 69% more than the out connection group and the diamond group. This result shows different ramp configurations might influence the exit ramps in different ways and the free-flow ramp would have more chances to occur crashes. The conclusion is consistent with previous studies (1, 3, and 5). In the past researches (1, 3), diamond ramps had the best safety performances comparing to other ramp configurations. But the out connection ramps have less average crash rate than the diamond ramps. This might be the reason that the out connection ramps in Florida are widely used as the freeway interchanges that have high design standards than normal exits. These improved standards might be better sign locations before and after the entrances of exit ramps,

better road conditions, or less variations along the exit ramps. Table 13 also listed the detailed statistical analysis results such as the total crashes per year, mean value, median value, and max and min values for each group in the exit ramp sections. For the loop exits, parclo loop ramps reported 16.7% less average crash rate than free-flow loop exit ramps.

**Table 13. Summary of Average Crash Frequency and Crash Rate for Four Exit Ramp Configurations**

Type	Crash Frequency (No. of crashes per year)				Crash Rate (No. of crashes per million vehicles per mile)			
	D	O	F	P	D	O	F	P
No. of Sites	247	93	26	23	247	93	26	23
Total No. of Crashes	544	216	57	23	544	216	57	23
Average No. of Crashes	2.20	2.32	2.21	1.00	3.47	2.24	5.86	4.88
Standard Deviation	2.46	3.44	2.20	1.09	6.35	3.89	8.33	8.9
Median	1.33	1.33	2	0.67	1.86	0.85	2.16	2.20
Max	11	22	8	4	77.11	22.25	37.28	41.51
Min	0	0	0	0	0	0	0	0

In order to compare whether the average crash frequencies and crash rates for the four exit ramp configurations have significant differences from each one, hypothesis tests were used to evaluate two populations. For example, the statistical Z or t test of average

crash rates for the diamond ramp group and the out connection ramp group was performed as following:

- 1) The mean values for two populations the diamond exit ramp and the out connection exit ramp are  $\mu_1$  and  $\mu_2$ ;
- 2) Mean value and standard deviation for the diamond exit ramp configurations are 3.47 and 6.35, while those for the out-connector exit ramp are 2.24 and 3.89;
- 3) 247 sites are diamond exit ramps and 93 sites are out connection sites;
- 4) The null hypothesis is  $H_0: \mu_1 = \mu_2$ , the alternative hypothesis is  $H_a: \mu_1 \neq \mu_2$ ;
- 5) Assuming the difference in the sample means of the two population fit the normal distribution and 90% confidence level was chosen for this study;
- 6) 
$$Z_0 = \frac{|3.47 - 2.24|}{\sqrt{\frac{6.35^2}{247} + \frac{3.89^2}{93}}} = 4.97 ;$$
- 7) The critical value for  $Z_{\alpha/2}$  is 1.645 which is smaller than 4.97 so that the null hypothesis is rejected.
- 8) The conclusion could be got as the average crash rate for the diamond exit ramps and the out-connector exit ramps is significant different at 90% confidence level.

The average crash frequency and crash rate for each population were tested at a 90% confidence level. Considering the sample size for parclo loop group is less than 25, t tests were chosen to use for this particular group as mentioned in the methodology parts. The basic procedures are same instead of the functional form which has been described in the methodology part. Table 14 listed all the results for the hypothesis tests. The comparison of the average number of crashes for the diamond exit ramps and the out

connection exit ramps showing “D:O” is significantly different at 90% confidence level meaning “YES” in the table. For average crash rate, the out connection exit ramps have significant difference to the other three configurations. The out connection ramps have the least average crash rate so that it has the best safety performance among the four exit ramp configurations at 90% confidence level. The free-flow ramps have the highest average crash rate and the hypothesis tests documented this ramp configuration appears more dangerous than the diamond ramps and out connection ramps. However, the difference between the free-flow ramps and parclo ramps is not significant at 90% confidence level.

**Table 14. Statistical Hypotheses Tests of Average Crash Frequency and Crash Rate for Four Exit Ramp Configurations**

Crash Type	Statistics for Two Mean Tests: 90%					
	D:O	D:F	D:P	O:F	O:P	F:P
Frequency	NO	NO	YES	NO	YES	YES
Rate	YES	YES	NO	YES	YES	NO

### **5.3.2 Target Crash Types**

Three target crash types that have the three highest crash numbers, rear-end crashes, angle crashes and sideswipe crashes, were compared for each ramp configuration among the four exit ramp configurations types. Table 15 lists the total numbers of target crashes, percentages of target crashes to total crashes, average crash numbers, standard deviations and median values for the four configurations by three target crash types.

The average crash numbers for rear-end crashes and angle crashes among the four configurations have larger differences between each other while the sideswipe crashes have minor distinction among the four configurations. In Table 16, the average crash rates for diamond ramps have highest per million vehicles per mile per year for rear-end crashes. Free-flow ramps have a little higher average crash rate than the other three configurations for angle crashes and sideswipe crashes. This is because diamond interchanges did not include large curves and most of crashes happened by the operating speed differences between vehicles. But the loop ramps such as free-flow loops have a 360 degree changing on the ramp sections alliance. Usually post or suggested speed limits on these ramps are smaller than diamond ramps, the causation of crashes are more related to the large variations of the alignments on the ramp itself. This geometric design feature lead to more angle and sideswipe crashes on the free-flow ramps.

**Table 15. Summary of Average Crashes Numbers by Target Crash Types  
for Four Exit Ramp Configurations**

Crash Severity	Statistics	D	O	F	P
Rear-end Crashes	No. of Crashes (% of Total)	274 (50.37%)	80 (37.04%)	14 (24.56%)	8 (34.78%)
	Average No. of Crashes	1.11	0.96	0.54	0.35
	Standard Deviation	1.71	1.78	2.48	1.58
	Median	0.4	0.33	0	0
Angle Crashes	No. of Crashes (% of Total)	44 (8.81%)	19 (8.80%)	13 (22.81%)	1 (4.35%)
	Average No. of Crashes	0.18	0.20	0.50	0.04
	Standard Deviation	0.24	0.17	0.36	0.11
	Median	0.18	0	0	0
Sideswipe Crashes	No. of Crashes (% of Total)	30 (5.50%)	10 (4.63%)	11 (19.30%)	2 (8.70%)
	Average No. of Crashes	0.15	0.11	0.42	0.09
	Standard Deviation	0.32	0.3	0.22	0.16
	Median	0	0	0	0

**Table 16. Summary of Average Crash Rates by Target Crash Types for  
Four Exit Ramp Configurations**

Crash Severity	Statistics	D	O	F	P
Rear-end Crashes	Average No. of Crashes	1.52	0.61	0.59	0.67
	Standard Deviation	2.78	1.31	1.23	1.01
	Median	0.43	0	0	0

**Table 16 (Continued)**

Angle Crashes	Average No. of Crashes	0.29	0.19	0.90	0.06
	Standard Deviation	0.26	0.66	0.76	0.21
	Median	0	0	0	0
Sideswipe Crashes	Average No. Of Crashes	0.28	0.05	0.76	0.11
	Standard Deviation	0.45	0.16	0.98	0.32
	Median	0	0	0	0

Proportionality tests were then conducted to compare the percentages of difference among the ramp configuration groups. The procedures of proportionality tests are mentioned before in the diverge areas. For example, the portions in rear-ends crashes for the diamond exit ramps and the out connection exit ramps were tested as follows:

- 1) The two populations of the diamond exit ramps and the out-connector exit ramps have the percentages of rear-end crashes to the total crashes  $p_1$  and  $p_2$ ;
- 2) The percentages of rear-end crashes to the total crashes for the two samples of Type 1 exit ramp and Type 2 exit ramp are  $\hat{p}_1$  and  $\hat{p}_2$ ;
- 3) 247 sites are diamond exit ramps and 93 sites are out connection sites;
- 4) The null hypothesis is  $H_0: p_1 - p_2 = 0$ , the alternative hypothesis is  $H_a: p_1 - p_2 \neq 0$ ;
- 5) Assuming the difference of proportions for rear-end crashes in the sample fit the normal distribution and 90% confidence level was chosen for this study;

$$6) Z^* = \frac{|50.37 - 37.04|}{\sqrt{\frac{50.37(100 - 50.37)}{247} + \frac{37.04(100 - 37.04)}{93}}} = 2.25;$$



- 7) The critical value for  $Z_{\alpha/2}$  is 1.645 which is much larger than  $Z^*$  so that the null hypothesis can be rejected;
- 8) The conclusion is the proportions of rear-end crashes for the diamond exit ramps and the out-connector exit ramps is significantly different at a 90% confidence level.

Table 17 exhibited all the statistical tests results for target crash types of exit ramp configurations. The diamond exit ramps have significant higher average rear-end crash rate than the other three types at 90% confidence level; while free-flow loop exit ramps have higher the average crash rates for angle and sideswipe crashes than the diamond exit ramps and out connection exit ramps. But the free-flow loop exit ramps and parclo loop exit ramps did not have significant difference on average sideswipe crash rate. This conclusion is consistent with the reason mentioned above as loop exit ramps have more opportunities occurring sideswipe crashes due to the continuous changeable on the ramp.

**Table 17. Z Statistics for Proportionality Tests by Target Crash Types for Four Exit Ramp Configurations**

Crash Type	Z Statistics for Proportionality Tests					
	D: O	D:F	D:P	O:F	O:P	F:P
Rear-end	YES	YES	YES	YES	NO	NO
Angle	NO	YES	NO	YES	NO	YES
Sideswipe	NO	YES	NO	YES	NO	NO

### 5.3.3 Crash Severity

Summary statistics for crash severity for different exit ramp configuration groups are given in Table 18 and 19. Even free-flow loop and parclo loop exit ramps have less average crash frequency for crash severity than the other two configurations. They both have higher average crash rates on crash severity and percentages in injury/fatality crashes to total number of crashes.

**Table 18. Summary of Average Crash Numbers by Crash Severity for Four Exit Ramp Configurations**

Crash Severity	Statistics	D	O	F	P
PDO	No. of Crashes (% of Total)	305 (56.07%)	119 (55.09%)	20 (35.09%)	8 (34.78%)
	Average No. of Crashes	1.23	1.28	0.77	0.35
	Standard Deviation	1.44	1.61	1.12	1.69
	Median	0.7	0.67	0.24	0.60
Injury/ Fatality Crashes	No. of Crashes (% of Total)	239 (43.93%)	97 (44.91%)	37 (64.63%)	15 (65.22%)
	Average No. of Crashes	0.97	1.04	1.42	0.65
	Standard Deviation	1.21	1.15	1.30	0.69
	Median	0.30	0.67	1	0.40

**Table 19. Summary of Average Crash Rates by Crash Severity  
for Four Exit Ramp Configurations**

Crash Severity	Statistics	D	O	F	P
PDO	Average No. of Crashes	1.91	1.12	3.16	2.06
	Standard Deviation	3.96	2.17	4.39	5.14
	Median	0.93	0.30	1.65	0
Injury/ Fatality Crashes	Average No. of Crashes	1.56	0.99	2.70	2.82
	Standard Deviation	2.69	2.04	4.27	4.79
	Median	0.74	0.32	0.79	0.94

Proportionality tests were also conducted to test the differences in crash severity among different configuration groups. The null hypothesis of the proportionality test is that the percentages of PDO or injury plus fatality crashes in different groups are equal. The results of Z statistics for the proportionality tests are listed in Table 20. The calculating procedures are as same as target crash type mentioned above. Based on the Z statistic tests, there is no evidence to reject the null hypothesis with 90% level of confidence. The results suggest that the impacts of different exit ramp configurations on crash severity are statistically significant especially for those loop exit ramps and non-loop exit ramps. Free-flow loop exit ramps and parclo loop exit ramps have higher percentage of injury plus fatality crashes but less percentage of PDO crashes comparing to diamond exit ramps and out connection exit ramps at 90% confidence level. Loop exit ramps seem to have more chances occurring high severity crashes. This is reasonable as angle and sideswipe crashes usually cause higher crash severity than rear-end crashes.

**Table 20. Z Statistics for Proportionality Tests by Crash Severity for  
Four Exit Ramp Configurations**

Crash Type	Z Statistics for Proportionality Tests					
	D:O	D:F	D:P	O:F	O:P	F:P
PDO	NO	YES	YES	YES	YES	NO
Injury/fatal	NO	YES	YES	YES	YES	NO

### 5.3.4 Crash Predictive Models

Another crash prediction model was developed to identify the factors that contribute to the crashes reported at selected exit ramp segments. Considering the available data source, a total of 388 observation sites were included in the model. One site did not have ramp design speeds which were believed significantly important to crashes. The dependent variable of the model is the average crash frequency per year reported at selected exit ramp sections. Nineteen independent variables were initially considered when building the crash prediction model. The initially selected independent variables are described in Table 21. The value of each variable are also listed in the table. The four exit ramp configurations were defined as three indicator variables.

The crash modeling starts from a Poisson model. For an adequate model, the scaled deviance and Pearson's  $\chi^2$  divided by the degrees of freedom shall be close to one. These two values are used to detect overdispersion or underdispersion in the Poisson regression model. Values greater than 1 indicate overdispersion, while values smaller than 1 indicate underdispersion. In this study, the Pearson's  $\chi^2$  divided by the degrees of freedom was found to be 5.84, indicating the fact that the crash data are overdispersed

and NB models shall be used. Stepwise regression method was used to select independent variables in the model. Eight variables were not found to be statistically significant. As a result, these variables were not included into the model. The best model contains eleven independent variables. The regression results of the best model are given in Table 22. As shown in the table 22, the scaled deviance and Pearson's  $\chi^2$  divided by the degrees of freedom are 1.18 and 1.06 which are reasonably close to one, indicating the fact that the model is adequately fitted. The final equation of the model is given as follows:

$$Y = \exp(-1.0721 - 0.2253X_1 + 0.4392X_2 + 0.2973X_3 - 0.2608X_4 - 0.0062X_5 + 0.6861X_6 + 0.3679X_7 + 0.2470X_8 - 0.0978X_9 + 0.0129X_{10} + 0.0580X_{11}) \quad (23)$$

Where, Y = expected average crash frequency in an exit ramp section (crashes/year),

$X_1$  = 1 if the site has an out connection exit ramp, 0 others;

$X_2$  = 1 if the site has a free-flow loop exit ramp, 0 others;

$X_3$  = 1 if the site has parclo loop exit ramp, 0 others;

$X_4$  = Length of the entire exit ramp (mile);

$X_5$  = Number of lanes on the ramp sections;

$X_6$  = 1 if the number of lanes widening after the entrance of exit ramps, 0 no;

$X_7$  = Upstream distances between exit ramp terminal and first intersection (mile);

$X_8$  = ADT per year in thousands on exit ramp sections;

$X_9$  = Ramp shoulder width (mile);

$X_{10}$  = Post speed limit on mainline (mph);

$X_{11}$  = Post or suggested speed limit on exit ramp sections (mph);

**Table 21. Description of Initially Considered Independent Variables  
on Exit Ramp Sections**

Independent Variable	Value	Frequency
Out-connector exit ramp	1 out-connector exit ramp 0 Otherwise	93
Free-flow loop exit ramp	1 free-flow loop exit ramp 0 Otherwise	26
Parclo loop exit ramp	1 parclo loop exit ramp 0 Otherwise	23
Number of lanes on mainline	1 One lane on mainline 2 Two lanes on mainline 3 Three lanes on mainline ..... n N lanes on mainline	388
Length of entire ramp	Distance for the entire ramp from the painted nose to the end of ramp (mi)	388
Number of lanes on exit ramps	1 One lane on mainline 2 Two lanes on mainline 3 Three lanes on mainline ..... n N lanes on mainline	388
Widening	0 No widening on the ramp 1 Exit ramp widening on the exit ramp Section	388
Signal	0 No signal control 1 Signal control Ramp terminal	388
Channalization	0 No channalization 1 Ramp terminal is channalization	388
Secondary upstream intersection	Distance between ramp terminal and the first upstream intersection	388
Secondary downstream intersection	Distance between ramp terminal and the first downstream intersection	388
ADT per year in thousand on exit ramp sections	Average ADT in thousands for three years 2004~2006	388

**Table 21 (continued)**

Road surface condition	0 Dry 1 Wet	388
Land type	0 Primarily business 1 Primarily residential	388
Road surface type	0 Blacktop 1 Concrete	388
Right shoulder type	0 Paved 1 Unpaved	388
Right shoulder width	Width for the right shoulder (ft)	388
Post speed on mainline	Maximal speed limit (mi/h)	388
Post or suggested speed on ramp	Maximal speed limit (mi/h)	388

**Table 22. Regression Results for Crash Prediction Model for Exit Ramp Sections**

Criteria for Goodness of Fit			
Criteria	DF	Value	Value/DF
Deviance	375	441.8539	1.1783
Scaled Deviance	375	441.8359	1.1783
Pearson Chi-Square	375	397.9857	1.0613
Scaled Pearson	375	397.9857	1.0613
Log Likelihood	3221.6867		

**Table 22 (continued)**

Analysis of Parameter				
Parameter	Coefficient	Standard error	$\chi^2$	Pr > $\chi^2$
Intercept	-1.0721	0.8577	0.6089	0.1113
Out-connect exit ramp	-0.2253	0.1577	0.0837	0.0530
Free-flow loop exit ramp	0.4392	0.2428	0.9150	0.0704
Parclo loop exit ramp	0.2973	0.2897	0.2704	0.0946
Length of entire ramp	-0.2608	0.3117	0.3502	0.0428
Number of lanes on exit ramp	-0.0062	0.1477	0.2833	0.0335
Widening	0.6861	0.1466	0.9732	<0.0001
Secondary Upstream	0.3679	0.1689	0.6990	0.0294
ADT in thousands on ramp	0.2470	0.0860	0.4155	0.0041
Should width	-0.0978	0.0775	0.0540	0.0266
Post speed limit on mainline	0.0129	0.0093	0.0311	<0.0001
Post or suggested speed limit on the ramp section	0.0580	0.0133	0.840	<0.0001
Dispersion	1.1143	0.0993		

All selected independent variables were statistically significant with a 90% confidence level. The coefficients of the model show that the crash counts at exit ramp sections increase with the mainline lane number, ramp ADT, post speed limit both on mainline sections and ramp sections, distances from ramp terminals to the first upstream intersection, and widening, but decrease with the ramp length, the exit ramp lane number,



and ramp shoulder type. With the increase of number of lanes on the exit ramp sections, the situation is different from diverge areas. Since more number of lanes on the ramp sections might diminish vehicle distributions on the ramp sections which are particular transition from freeway sections to the secondary roads. The desperation of vehicles would diminish conflict points on the ramp section. With long ramp length, the impacts of freeway diverge areas and secondary cross roads would be minimal, so fewer crashes would occur comparing these short distance ramps that both freeways and cross roads have influences on the ramp itself. With larger should width, drivers have more flexible spaces while dangerous situations happened especially for loop exit ramps that need more space to avoid angle and sideswipe crashes.

ADT exit ramp sections would increase the opportunities occurring crashes. It is consistent with previous studies. Post speed limits both on mainline and ramp sections have positive influences on the crashes. Since ramp speed is much lower than freeway segments, such as 25-40 mph, drivers would continually maintain high speed on the ramp section while the post speed limit is high; however usually ramp sections did not have a high design standard comparing to freeways. This would mistake drivers so that chances of having potential crashes would rise. Another two positive variables are the widening conditions and distance from ramp terminals to first upstream intersection. It is institutive that widening would cause more merging or diverging maneuvers which were generally the main reasons of happening crashes. The coefficient of distance from ramp terminals to first upstream intersection is 0.3679 which has a significant increase in crash frequency while the increasing the distances. It means if the intersection is far away the ramp terminals, it would raise the chances of happening crashes. If the intersection is nearby

the ramp terminals, more attentions would paid at those intersection areas as most drivers are more sensitive to intersections than the normal driveways or roadways.

The coefficients for the three indicator variables have different signs, indicating the fact that the site with the out connection exit ramp has the least numbers of crashes. This conclusion is consistent with the result of our cross-sectional comparison. The coefficients of the model can be used to quantify the safety impacts of different exit ramp configurations. Based on the model, the sign of out connection exit ramp is negative. It can concluded that replacing a diamond exit ramp with an out connection exit ramp, will reduce crashes in the sections by  $\exp(0.2253)-1=26.90\%$ . However, replacing a diamond exit ramp with a free-flow loop ramp and a parclo loop ramp will increase crash counts at exit ramp by  $\exp(0.4392)-1=56.86\%$ , and  $\exp(0.2973)-1=35.62\%$ . Thus, we can calculate the increasing percentages for replacing an out connection exit ramp with  $68.47\%$  and  $48.72\%$ . While only concerning on the loop exit ramp, replacing a parclo loop exit ramp with a free-flow loop exit ramp would increase crash counts by  $\exp(0.4392-0.2973)-1=15.66\%$ .

## **CHAPTER SIX**

### **SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

#### **6.1 Summary**

The objective of this study is to evaluate the impacts of different exit ramp types on the safety performance. Two research subjects, freeway diverge areas and exit ramp sections, were selected. Impacts of different exit ramp types on the diverge areas and different ramp configurations on the exit ramps were analyzed respectively. This study developed quantitative evaluations and comparisons on the freeway diverge areas and exit ramp sections correspondingly. The results of this study will help transportation decision makers develop tailored technical guidelines governing the selection of the optimum exit ramp types to be used on our freeways and exit ramps.

For the freeway diverge areas, in order to find the impacts of exit ramp types on the safety performance of freeway diverge areas, lane balance issues were considered to determine the exit ramp types on the freeway diver areas. The exit ramp types were defined by the number of lanes used by traffic to exit freeways. Four different types of exit ramps were considered in this study. For convenience, they are defined as Type 1, Type 2, Type 3, and Type 4 exit ramps. Among these exit ramp types, Type 1 and Type 2 are one-lane exit ramps, while Type 3 and Type 4 are two-lane exit ramps. Type 1 is a parallel from a tangent single-lane exit ramp. Type 2 is a single-lane exit ramp without a

tangent. Type 3 is a two-lane exit with an optional lane and Type 4 is a two-lane exit without an optional lane. A total of 424 freeway segments were collected in the State of Florida, 220 sites for Type 1 exit ramps, 96 sites for Type 2 exit ramps, 77 sites for Type 3 exit ramps and 31 sites for Type 4 exit ramps. The selected sites were divided into four groups based on the types of exit ramps. Crash data were selected for three years, from 2004 to 2006 for each site. Cross-sectional comparison was conducted for comparing the crash frequency, crash rate and crash severity between different exit ramp groups. Three target crash types that have the three most crashes were chosen from all the crash types. They are rear-end crashes, sideswipe crashes and angle crashes. The average crash number and crash rate was calculated by each exit ramp type on each freeway diverge site. The hypothesis tests were conducted for four exit ramp types to compare whether significant differences for average crash frequency and crash rate are present between the four exit ramp types at 90% confidence level. Crash severity was grouped by two categories, property-damage-only crashes and injury/fatality crashes for four exit ramp types. The average crash frequency and crash rate for each target crash type and crash severity were calculated by four exit ramp types on the freeway diverge areas as well. Proportionality tests were performed for the target crash types and two crash severity categories by four exit ramp types. A crash prediction model containing 404 sites was developed to identify the factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of different freeway exit ramps.

On the exit ramp sections, the exit ramp configurations were grouped by four regular categories, which are diamond exit ramps, out connection exit ramps, free-flow loop exit ramps and parclo loop exit ramps. A total of 389 exit ramp sites were collected

in the State of Florida, 247 sites for the diamond exit ramps, 93 sites for the out connection exit ramps, 26 sites for the free-flow loop exit ramps and 23 sites for the parclo loop exit ramps. Crash data were selected for the same years in the diverge areas, from 2004 to 2006 for each site. Cross-sectional comparison was also conducted for comparing crash frequency, crash rate and crash severity between different exit ramp configuration groups. Rear-end crashes, sideswipe crashes and angle crashes are the target crash types that have the three most crashes among all the crash types. Crash severity was grouped by two categories, property-damage-only crashes and injury/fatality crashes. The hypothesis tests were completed respectively at 90% confidence level. A negative binomial crash prediction model including 388 sites was developed to identify the factors that contribute to the crashes reported at selected exit ramp segments.

## **6.2 Conclusions**

In this thesis, two research parts, freeway diverge areas and exit ramp sections are analyzed separately. The conclusions would describe separately for the two parts.

### **6.2.1 Freeway Diverge Areas**

Based on the research analysis, the conclusions on freeway diverge areas can be obtained as following:

- 1) Type 1 exit ramp has the best safety performance in terms of the lowest crash frequency and crash rate on freeway diverge areas. However, statistical tests show that crash severity and crash types did not have significant differences among the four exit ramp types on the freeway diverge areas at 90% confidence level.

- 2) The predictive model was built. The coefficients of the model show that the crash counts at freeway diverge areas increase with the mainline lane number, the deceleration lane length, mainline ADT, ramp ADT and post speed limit difference between mainline sections and ramp sections, however decrease with the entire ramp length, post speed limit on mainline sections and surface type.
- 3) The model also quantifies the impacts of different exit ramp types. For one-lane freeway exit ramp, replacing a type 1 exit ramp with a type 2 exit ramp will increase crash counts at freeway diverge area by 15.57%. For two-lane exit ramps, replacing a type 3 ramp with a type 4 ramp will increase crash counts at freeway areas by 10.80%.

### **6.2.2 Freeway Exit Ramp Sections**

Summary of safety evaluation on exit ramp sections were given in following conclusions:

- 1) The results of average crash rates on four ramp configurations show that the out connection group has the best safety performance. The free-flow loop group has more dangerous in terms of the greatest average crash rate comparing to the other three exit ramp types.
- 2) Statistical tests suggest that the loop exit ramps have significant higher crash severity level than non-loop exit ramps at 90% confidence level. Three target crash types, which have the three highest crash numbers, are rear-end crash, angle crash and sideswipe crash. Diamond exit ramps have significant higher average rear-end crash than the other three types; while free-flow loop exit ramps have higher average crash rates for angle and sideswipe crashes than the non loop exit ramps.

- 3) The coefficients of the model show that the crash counts at exit ramp sections increase with the mainline lane number, ramp ADT, post speed limit both on mainline sections and ramp sections, distances from ramp terminals to the first upstream intersection, and widening, but decrease with the ramp length, the exit ramp lane number and ramp shoulder type.
- 4) The coefficients for ramp configurations indicate the fact that the site with the out connection exit ramp has the least numbers of crashes. Based on the model, replacing an out connection exit ramp with a diamond exit ramp, a free-flow loop ramp and a parclo loop ramp will increase crash counts at exit ramp sections by 26.90%, 68.47%, and 48.72%. For the loop exit ramp, replacing a parclo loop exit ramp with a free-flow loop exit ramp would increase crash counts by 15.6%.

## **6.3 Applications and Recommendations**

### **6.3.1 Applications**

This study conducted statistical methods and tests to evaluate safety performances of freeway exit ramps on two parts, freeway diverge areas and exit ramp sections. On the freeway diverge areas, four typical exit ramp types used in Florida were compared and it was found that a parallel from a tangent single-lane exit ramp has the best safety performances among the four exit ramp types. On the exit ramp sections, four widely used exit ramp configurations were selected and compared in the State of Florida. The study provided technical specifications for transportation agencies to develop tailored guidelines or practical design instructions. Transportation engineers, researchers and investigators would benefit from the study as well. The contributing factors to crashes

and their impacts were identified and concluded. The results of this study would help transportation decision makers select the optimal exit ramp types and design combinations in our freeway mainline segments under different site situations.

### **6.3.2 Recommendation**

Four types of freeway exit ramps were considered on the freeway diverge areas, the crash data analysis results between one lane exit ramps (Type 1 and Type 2 exit ramps) and two-lane exit ramps (Type 3 and Type 4 exit ramps) confirm the general assumption that lane balanced exit ramps would be safer than those not lane balanced exit ramps on the freeway diverge areas (12). In practice, however, there is also a type 5 exit ramp which is a two-lane exit ramp without optional lane and without a taper. This exit ramp is not widely used in Florida and the samples we found are too small to draw defensible conclusions.

To select the optimal exit ramp type, the safety performance of freeway ramp section, more study need to focus on ramp terminal design and control and the diverge deflection angle. These two variables are very important factors which need to be considered more specific. The authors recommend that future studies could be made on these issues.

Another important consideration is the conflict studies on these sites to further refine the methodology. In addition, operational analysis and simulation analysis need to be applied. Operational impact and safety impacts should look closely to determine the practical design for both freeway diverge areas and exit ramp sections.



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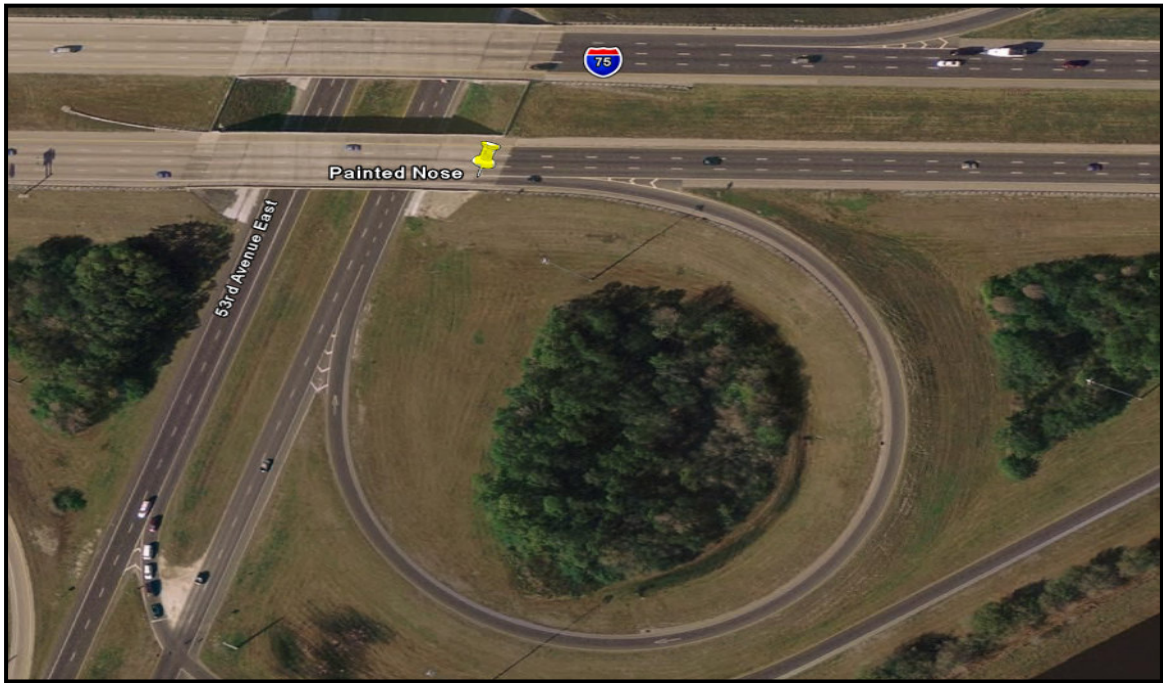
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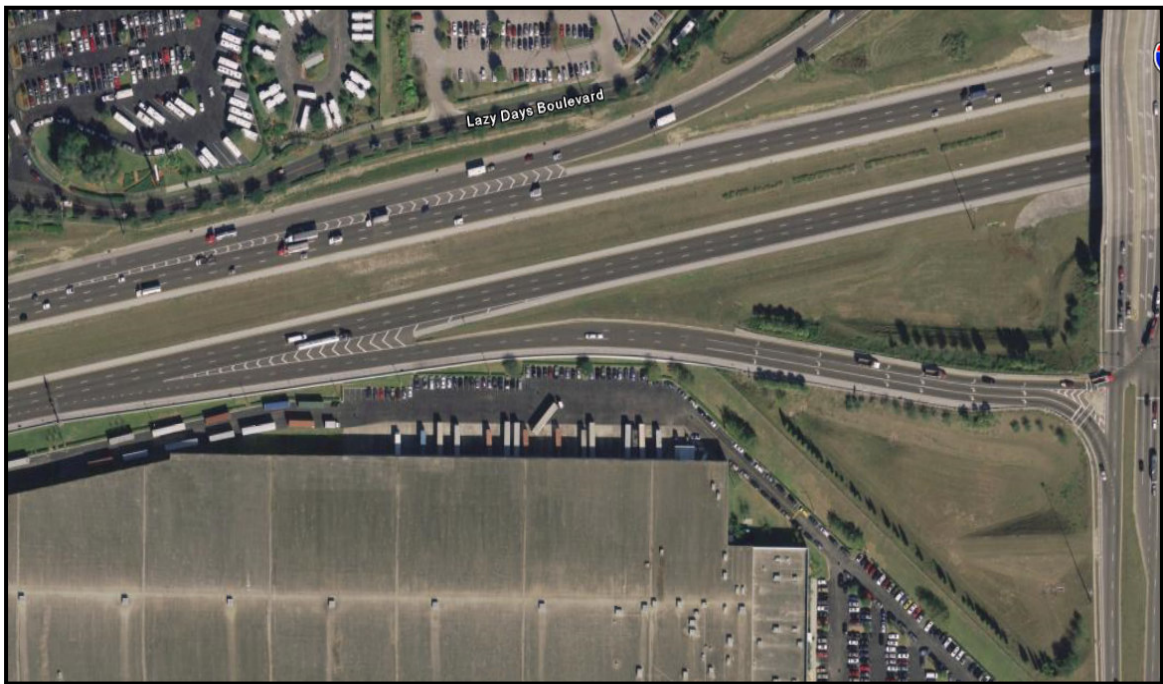
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## **APPENDICES**

## Appendix A: Site Picture Examples



**Type 2 Exit Ramp with Parcolo Configuration**



**Type 3 Exit Ramp with Diamond Configurations**



**Type 1 Exit Ramp with out connection Configuration**



**Type 2 Exit Ramp with Parclo Loop Configuration**