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Comparison of Safety Performance by Design Types at Freeway Diverge Areas and Exit Ramp Sections

Hongyun Chen
University of South Florida

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Diverge Areas and Exit Ramp Sections

by

Hongyun Chen

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Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Co-Major Professor: Yu Zhang, Ph.D.
Co-Major Professor: Jian John Lu., Ph.D.
Abdul Pinjari, Ph.D.
Lakshminarayan Rajaram, Ph.D.
Michael Weng, Ph.D.

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DEDICATION

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

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ABSTRACT

The primary objective of the study is to evaluate the safety performance of different freeway exit types used in current practical designs. More specific, the research objectives include the following two parts: 1) to compare the safety performance of different design types at freeway diverge areas and exit ramp sections; and 2) to identify the impact factors contributing to the crashes happening at these two specific segments.

The study area includes four subjects, the freeway widely-spaced diverge areas; the freeway closely-spaced diverge areas; the left-side off-ramps and the exit ramp sections. For the freeway diverge areas, design types were defined based on the number of lanes used by vehicular traffic to exit freeways and lane-balance theory. Four exit ramp types were considered for the widely-spaced diverge area, 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 closely-spaced diverge areas, three types, named as Type A, Type B and Type C, are selected to compare the safety performances among the three types. For the left-side off-ramp at the freeway diverge area, this study examined the two most widely used design types at the left-side freeway diverge areas in Florida, which are defined as Type I (one-lane left-side off-ramp), and Type II (two-lane left-side off-ramp). Type I is comparable to Type 1 design type and Type II is comparable to Type 3 design type at widely-spaced freeway diverge area. 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 the crash frequency, the crash rate, the crash severity and target crash types between different design groups. Crash predictive models were also built to quantify the impacts of various contributing factors. The results of this study would expectedly help transportation decision makers develop tailored technical guidelines governing the selection of the optimum design combinations at freeway diverge areas and exit ramp sections.

CHAPTER 1

INTRODUCTION

1.1 Background

Freeways and the neighboring areas are the specific traffic facilities which are designed under the highest highway design standards. To achieve the design objectives, the highway system regulates traffic approaches by fully controlling the accesses. Exit ramps provide the only connection from freeways to the secondary crossroads which could be other freeways, major or minor arterials, or local collectors. Since exit ramps are the only control accesses for vehicle exiting freeways, freeway diverge areas in the vicinity of exit ramps are considered as one of the critical sections on freeways where intensive lane changing maneuvers due to exiting traffic always cause the disturbance to through traffic. This disturbance may produce traffic conflicts, increase the occurrence of potential crashes, and even aggravate the injury severity. It is benefit to improve the safety performance of freeway diverge areas and exit ramp sections by identifying the factors contributing to crashes and understanding the impacts of these factors. The factors may include different design types, various deceleration lengths, exiting lane numbers, design speeds, exit ramp configurations, road pavement conditions, etc.

Different design types would affect the safety and operation performances of the diverge areas and exit ramps in different ways. A Policy on the Design of Geometric Highways and Streets (AASHTO) (1) mentioned that composite design components

can 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 separate the traffics exiting from or continuing on the freeway mainlines. Different exit sides, such as right exits or left exits, will certainly require drivers take different maneuvers to leave or maintain on the freeways. The distance between the on-ramps and off-ramps is another important factor. For example, if the on-ramps and off-ramps are closely nearby, the entrance vehicles need merge to the mainline sections while the exiting vehicles need diverge from the mainline sections. The mixed lane-changing vehicles increase the potential conflicts and may cause the occurrences of severe crashes. These influential factors at the diverge areas needed to be identified and clarified.

The exit ramp section is one of the major highway facilities. Exit ramps provide limited accesses from freeways to other highway systems, arterials or local streets. "Ramp Management and Control Handbook" (2), published by U.S. Department of Transportation (DOT) and Federal Highway Administration (FHWA) in 2004, aims to manage ramp policies, strategies and technologies to improve safety on the exit ramp and the influential areas. Ramp management strategies control the traffic both on the exit ramps and 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.

Several different design types are currently used at the freeway diverge areas and exit ramp sections. Better understanding the affects of design types would help improve the safety, mobility, accessibility, and operation aspects for both freeways diverge areas and exit ramp sections.

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1.2 Problem Statement

Drivers exiting freeways need make several maneuvers such as reducing vehicle speeds, finding appropriate gaps, changing lanes, or diverging to deceleration lanes. While closely-examined the freeway diverge area, the situations are different while the distance between an entrance ramp and the successive exit ramp is widely-spaced or closely-spaced. For example, while entrance and exit ramps on the right side are widely spaced (i.e., the distance between the painted nose of the exit ramp and the merge point of the upstream entrance ramp is greater than 0.5 mile), merging vehicles from entrance ramps do not apparently affect traffic at freeway diverge areas.

However, the situations for the widely-spaced diverge areas cannot be accommodated to the situation where the right entrance and exit ramps are closely-spaced without further investigation. The merging influential area in vicinity of the entrance terminal is sometimes overlapped with the diverging influential area around the painted nose of the exit ramp. The entering traffic will merge to the left to join the approaching traffic, while the exiting traffic will merge to the right to exit the freeway. The presence of approaching freeway vehicles, merging vehicles and diverging vehicles within a relatively short freeway segment creates more complex driving environments as compared to the situation where entrance and exit ramps are widely spaced. As a result, the two situations need be discussed separately.

The number and arrangement of lanes used by traffic to exit freeways on the diverge area are important considerations in freeway mainline design. In the current practical engineering applications, two principles are being used by transportation professionals to determine the number and arrangement of lanes on freeway mainlines

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and ramps. They are 1) the consistency of basic number of lanes, and 2) the principles of lane balance. The principle of basic number of lanes is defined as the minimum number of lanes designated and maintained over a significant length of a freeway. According to the AASHTO Green Book (1), the basic number of lanes should be consistent for a substantial length of freeway, irrespective of changes in traffic volume and lane-balance needs.

Lane balance theory has been used extensively to determine the number of lanes approaching freeway entrance and exit ramps. Based on the lane balance theory, the number of lanes beyond two traffic streams should not be less than the sum of all traffic lanes on the merging roadways minus one, but may be equal to the sum of all traffic lanes on the merging roadway at entrances. At exits, the number of approach lanes on the highway should be equal to the number of lanes on the highway beyond the exit, plus the number of lanes on the exit, minus one (1). The principles of lane balance sometimes conflict with the desire to maintain continuity in the basic number of lanes. There are many different ways to coordinate the principles of lane balance and the consistency in the basic number of lanes. Different arrangements may have different impacts on safety performance of freeways and this is particularly true for the condition where an entrance ramp is closely followed by an exit ramp.

Based on the number and arrangement of lanes, freeway diverge areas, for example, the widely-spaced diverge situation and closely-spaced situation, have different design types. Different design types require drivers to make distinctive decisions to complete the maneuvers to exit or continue on the freeway. As a result, different design types will have different impacts on the safety and operation performance.

However, the impacts on the safety performance by various design types at freeway diverge areas have not been well studied or documented until recently. No conclusion on the safety evaluation has been drawn on this specific section through systematic research activities. At present, little documentation is available regarding the safety performance at the freeway diverge areas and no widely accepted guidelines are available regarding the coordination of lane balance and basic number of lanes for this particular segment.

Moreover, the safety performance of the abnormal left exits on freeways is even more uncertain. Left-side off-ramps are usually unexpected related to driver common expectation. The left exit off-ramp has much more safety concerns than the right exits at the freeway diverge areas. Left-side off-ramp is always considered as a critical design and AASHTO Green Book (1) indicates that this design type needed to be avoided in future design as compare to right-side exit ramps. The left-side off-ramp is very sensitive and can only be relocated at the first opportunity along existing corridors. Recently increasing traffic accidents on the left-side off-ramps on I-275 in Tampa FL raised the great concern on the safety effects of left-side off-ramps at the freeway diverge areas. The understanding on the difference of the safety performance between left-side off-ramps and right-side exit ramps is noticeably important. The problem is relatively new and the study is highly demanded in today's highway system.

On the exit ramp section, little focus has been on the safety issues for this specific segment. Different influential factors relating to the safety performance on entire exit ramp sections need be re-evaluated since previous studies have a few limitations. For example, some predictive crash models included the different ramp configurations and

ramp length; however the control types of ramp terminals were not contained in their studies (3). Some models combined the off ramps and on ramps; however, the combination of the two ramp types would ignore the differential operating maneuvers at these two segments. Existing vehicles on the exit ramps need decrease the travelling speed or maintain a relative lower speed than that on the freeway mainline section while vehicles on the entrance ramps continually increase speed to merge the freeway mainline areas.

In summary, this research study conducted comprehensive safety evaluations on freeway diverge areas and exit ramp sections respectively. Freeway diverge areas include widely-spaced diverge situations, closely-spaced situations, and left-side off-ramps. Different design types at the freeway diverge areas were defined according to the two principles, the consistency of basic number of lanes and the lane balance theory. The results of the study will help transportation decision makers develop tailored technical guidelines governing the selection of the optimum exit ramp types and combinations of correlated factors using on our freeway diverge areas and exit ramp sections.

1.3 Research Objective

The primary objective of the study is to evaluate the safety performance of freeway diverge area and freeway exit ramp section. More specific, the research objective can be divided into two parts, one for the freeway diverge area and one for the exit ramp section. At the freeway diverge area, three situations are identified, the widely-spaced situation, the closely-spaced situation and the left-side off-ramp. Following three goals are aimed to achieve:

1) Evaluate the safety performance by different designs at the widely-spaced diverge areas and identify the factors that contribute to crashes for this situation;

2) Define the current practical engineering design types at closely-spaced freeway diverge areas and compare the safety performance among the defined types;

3) Compare the crash records of those left-side and right-side off-ramps at the freeway diverge areas to investigate the safety performance of left-side off-ramps;

On the exit ramp sections, the safety performance by different exit types was evaluated and the contributing factors were recognized.

Statistical methods, statistical tests and crash predictive models, were applied in this study. Base on the results, it would be a plausible way to help judge what kind of geometric designs, traffic conditions, and the combinations of the correlated conditions, have the best safety performance at the freeway diverge areas and on the exit ramp sections. This is also a practical step to guide the safety improvement and potential counter-measurements on the study segments. Also, the results could be applied in current design guidelines, handbooks and future research projects.

1.4 Research Subject

While exiting freeways, vehicles must decrease speeds and weave to the deceleration lane toward the exit ramp. On the exit ramp sections, different ramp configurations, such as diamond, out connection, free flow, and parclo flow, might confuse drivers as well. Two subjects are discussed separately, the freeway diverge areas, including widely-spaced situations, closely-spaced situations and left-side off-ramps, and the exit ramp sections.

1.4.1 Freeway Diverge Areas

1.4.1.1 Widely-Spaced Situation

The widely-spaced diverge area is limited to the situation where entrance and exit ramps are widely spaced. In this situation, the distance between the painted nose of the exit ramp and the merge point of the upstream entrance ramp is greater than 0.5 mile. Merging vehicles from entrance ramps do not apparently affect traffic at freeway diverge areas. During the past several decades, researchers focused on developing crash prediction models on ramp sections or deceleration-lane sections by different explanatory variables. However, none of these studies has focused on the impacts of the number and arrangement of lanes used by traffic to exit freeways at freeway diverge areas.

Until recently, the safety impacts of the number and arrangement of lanes have not been well studied or documented. At the freeway diverge area, the one or two outer lanes may drop as 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. So the lane-balanced and unbalanced designs have dissimilar influences on safety. Even considering the lane balanced or the unbalanced designs respectively, different numbers of exit lanes have different characteristics as well. To evaluate and compare the impacts by various design types at the diverge area; the exit ramp types are defined by the number and arrangement of lanes used by traffic to exit freeways.

The exit ramp could be a single-lane exit or a two-lane exit. After reviewing the current design guidelines, the field sites in the Florida interstate highway systems, expressways, turnpikes and parkways, four types are frequently used. For convenience,

they are defined as Type 1, Type 2, Type 3, and Type 4. The four types are illustrated in Figure 1 to Figure 4 respectively. Detailed definitions of each type are described as follows:

1) Type 1 (parallel from a tangent single-lane exit ramp design 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 alignments of type 1 design type 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 though lane on the exit ramp section.

2) Type 2 (single-lane exit ramp without a taper design 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 for this type to provide a maneuver and recovery area. No additional lane was added when compared with Type 1.

3) Type 3 (two-lane exit ramp with an optional lane design shown in Figure 3): this type includes two exit lanes while a large percentage of traffic 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 (two-lane exit without an optional lane design shown in Figure 4): it is used where the outer lane is reduced and another full width parallel from tangent lane developed with a taper is forced to exit. It differs as from Type 3 exit ramps as Type 4 exit ramps do not enclose the optional lane.
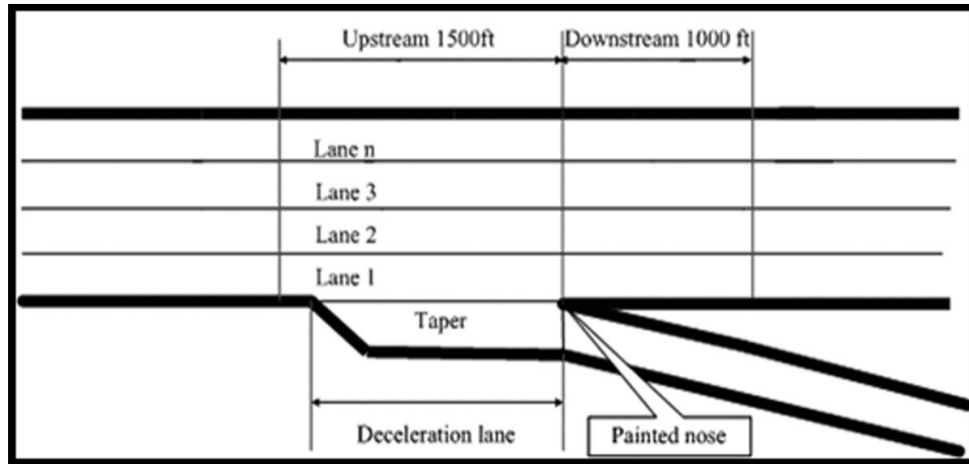
Figure 1 Type 1: Parallel from a Tangent Single-lane Exit Ramp Design
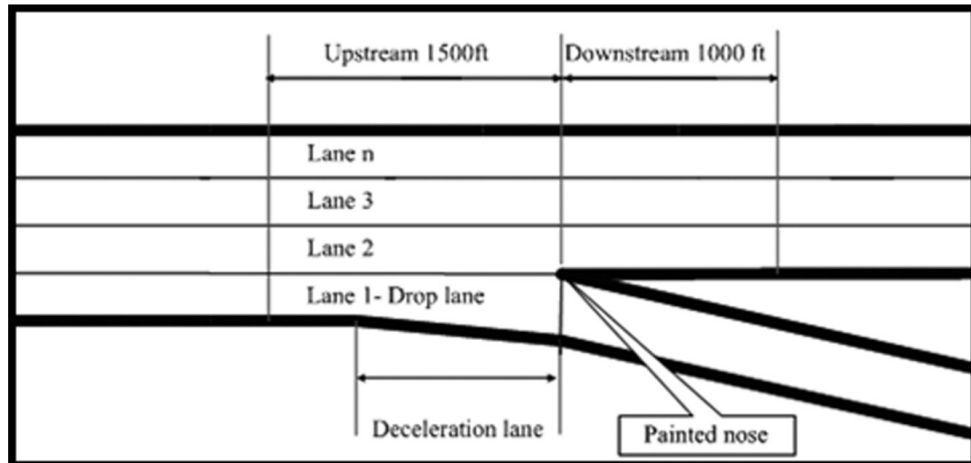
Figure 2 Type 2: Single-lane Exit Ramp without a Taper Design
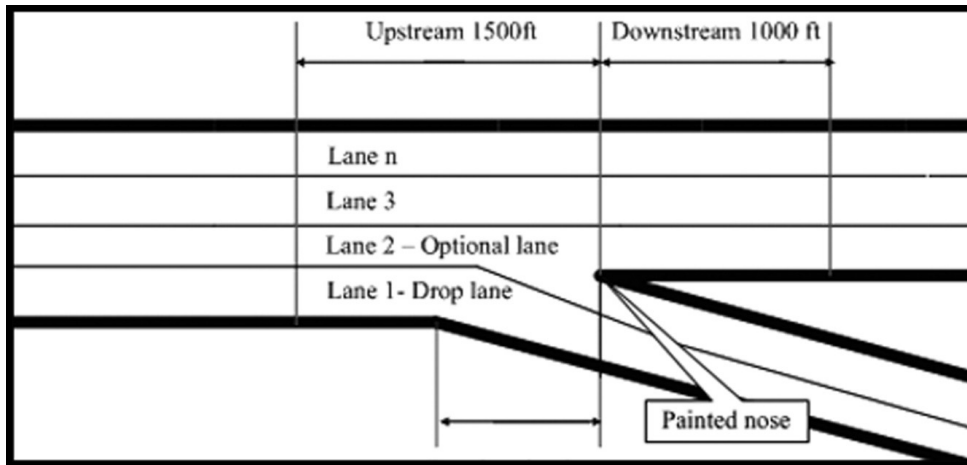
Figure 3 Type 3: Two-lane Exit Ramp with an Optional Lane Design
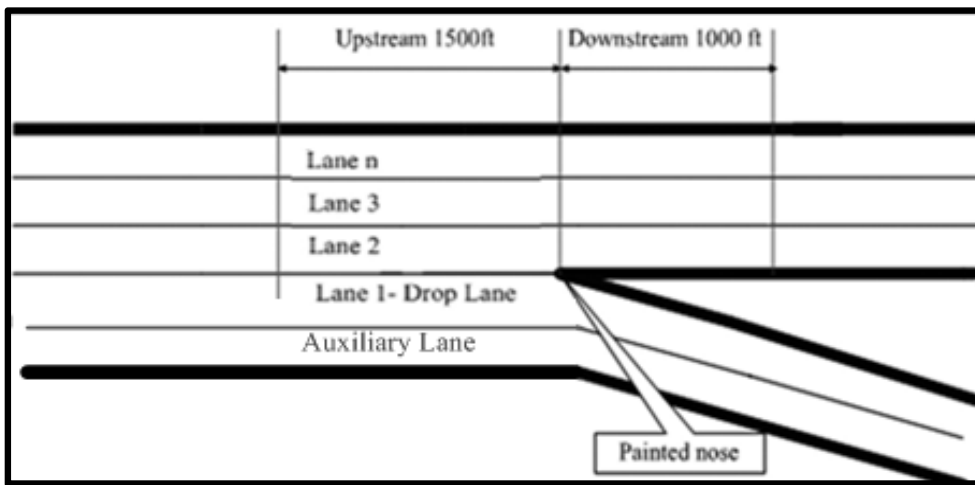
Figure 4 Type 4: Two-lane Exit Ramp without an Optional Lane Design

In summary, Type 1 and Type 2 are one-lane exit ramp designs while type 3 and type 4 are two-lane exit ramp designs. For both Type 2 and Type 4, a freeway main lane is dropped at the exit gore. Considering the lane balance theory, Type 1 and Type 3 are lane balanced designs while Type 2 and Type 4 are lane unbalanced designs. If the safety benefits of lane balance are valid, Type 1 and Type 3 designs should have better safety performance as compared to Type 2 and Type 4 designs.

1.4.1.2 Closely-Spaced Situation

If the distance between an entrance ramp and an exit ramp is closely, the merging area in vicinity of the entrance terminal is sometimes overlapped with the diverge area around the painted nose of the exit ramp. The entering traffic will merge to the left to join the approaching traffic, while the exiting traffic will merge to the right to exit the freeway. The presence of approaching freeway vehicles, merging vehicles and diverging vehicles within a relatively short freeway segment creates more complex driving environments as compared to the situation where entrance and exit ramps are widely-spaced.

The conclusions of the widely-spaced situation at the diverge area cannot be directly applied to the situation where entrance and exit ramps are closely-spaced without further investigation. At present, little documentation is available regarding the safety performance of the freeway segments with closely spaced entrance and exit ramps, and no widely accepted guidelines are available regarding the coordination of the lane balance theory and the principle of basic number of lanes for this particular situation.

To eliminate the impacts of various external factors that may affect safety of selected freeway segments and to focus on the impacts of the arrangement of lanes on freeway mainlines; the selected freeway segment should have a right entrance which is closely followed by a right exit. The distance from the merge point of upstream entrance to the painted nose of downstream exit is less than 0.5 mile.

Based on over 1,000 reviewed aerial photos and site plans were reviewed for freeway segments in the state of Florida. A total of 75 sites meet the criteria mentioned above and were selected for further investigation. It was found that 7 different types of arrangements are used in the current practical engineering applications. In Figure 5, they

are designated as Type A to Type G arrangements. The characteristics of these arrangements are briefly described as follows.

n	n	n	Type A (26 Sites)
1		1	Lane Balance: Yes
			Basic Number of Lanes: Consistent
n	n	n	Type B (18 Sites)
1	1	2	Lane Balance: Depends
			Basic Number of Lanes: Consistent
n	n	n	Type C (22 Sites)
1	1	1	Lane Balance: Depends
			Basic Number of Lanes: Consistent
n	n	n-1	Type D (1 Site)
1		2	Lane Balance: Yes
			Basic Number of Lanes: Not Consistent
n	n	n-1	Type E (3 Site)
1	1	2	Lane Balance: No
			Basic Number of Lanes: Not Consistent
n	n	n	Type F (3 Site)
2	2	2	Lane Balance: No
			Basic Number of Lanes: Consistent
n	n	n+1	Type G (2 Site)
2	2	2	Lane Balance: Yes
			Basic Number of Lanes: Not Consistent

Figure 5 Current Engineering Practical Closely-Spaced Ramp Designs

For the type A arrangement, a one-lane entrance ramp is closely followed by a one-lane exit. It is sometimes difficult to negotiate a parallel-type entrance or exit because of the limited space available between entrance and exit ramps. As a result, most of the selected sites with the type A arrangements are designed with taper-type entrances

and exits. For example, among the 26 sites with the type A arrangements, 21 sites are designed with taper-type entrances while only 5 of them are designed with parallel-type entrances. In addition, all exit ramps are taper-type exits. Considering the coordination of lane balance and the basic number of lanes, both lane balance theory and the consistency of basic number of lanes are maintained for this particular arrangement.

For the type B and type C arrangements, a continuous auxiliary lane connects the entrance and exit ramps. The continuous auxiliary lane serves as both an acceleration lane for the entrance ramp and a deceleration lane for the exit ramp. In this condition, a weaving segment is formed between the closely spaced entrance and exit ramps. The only difference between these two arrangements, Type B and Type C, is that a type B arrangement is ended with a two-lane exit while a type C arrangement is ended with a one-lane exit. Both type B and type C arrangements are consistent in terms of the basic number of lanes. Whether they are lane balanced designs depends on the length of the continuous auxiliary lanes.

According to the AASHTO Green Book (1), if the distance between the end of taper of the entrance area and the beginning of the taper of the exit area is less than 1500 ft, lane balance principles allow an auxiliary lane to be provided between the closely spaced entrance and exit ramps. The auxiliary lane can be dropped in a single-lane exit with the number of lanes on the mainline freeway being equal to the number of through lanes beyond the exit plus the lane on the exit. If the distance is greater than 1500 ft, lane balance principles require the auxiliary lane to be dropped in a two-lane exit. In the present study, the length of the auxiliary lanes at selected sites with the type B arrangements ranges from 898 ft to 2630 ft with a mean of 1695 ft. The length of the

auxiliary lanes at selected sites with the types C arrangements ranges from 422 ft to 2640 ft with a mean of 1845 ft. Thus, some of the sites with the type B and C arrangements are lane balanced while some of them are not.

For the type D arrangement, a one-lane entrance ramp is followed by a two-lane exit. The outer lane of the freeway is dropped at the exit gore. A taper is also provided to improve capacity of the exit ramp. Traffic on both the dropped lane and the taper are forced to exit the freeway. While the principles of lane balance are maintained, the type D arrangement is not consistent in terms of the basic number of lanes. The type E arrangement is similar to the type D arrangement. The only difference is that the type E arrangement is designed with a continuous auxiliary lane which connects the entrance and exit ramps. Neither the principle of lane balance nor the consistency in basic number of lanes is maintained for the type E arrangement.

Both the type F and type G arrangements are designed with a two-lane entrance ramp which is followed by a two-lane exit ramp. Two continuous auxiliary lanes connect the entrance and exit ramps. For a type F arrangement, both auxiliary lanes are dropped at the exit gore. For a type G arrangement, only the outer auxiliary lane is dropped at the exit, while the inside auxiliary lane becomes an optional lane. For the optional lane, traffic can either exit right or proceed straight ahead on the freeway. For the type F arrangement, the principles of lane balance are violated while the consistency in basic number of lanes is maintained. For the type G arrangement, the basic number of lanes is not consistent while the entrance and exit ramps are lane-balanced.

In this study, the type D, type E, type F, and type G arrangements were not selected for further crash data analysis because the sites found in the field were too few to

draw defensible statistical conclusions. Crash data analysis will be later only focus on the type A, B and C arrangements, which were found to be the most commonly used arrangements in the current engineering practices.

1.4.1.3 Left-Side Off-Ramp

To examine the impact of ramp locations on freeway segments, the safety performance of left-side off-ramps on the diverge areas is a specific but critical issue. A few past studies examined the factors that affect freeway off-ramp safety, however, few has evaluated the safety impacts of left-side off-ramps. The left-side off-ramps were long believed more dangerous than the right-side off-ramps under the same conditions. It needed be avoided in the future design.

The left-side off-ramp is rarely in most freeways so that the number of size is limited. The field observation from video recorded at 4 left-side off-ramps showed that the left-side off-ramps experienced more evasive maneuvers, such as applying brakes, swerving, or noticeably decelerating in order to avoid a conflict. Four basic conflicts often happen during the specific area, including diverging conflict, merging conflict, weaving conflict, and crossing conflict. Figure 6 to Figure 9 show the specific changing maneuvers at the freeway diverge area if the off-ramp is on the left side. Merging occurs between the first vehicle changing from the exit lane to the through lane and the following vehicle on the through lane to where the first vehicle is changing. It happens when the vehicle which intended to stay on the freeway but travelled on the exit lane erroneously. To keep moving on the freeway, the vehicle needs to make a lane change maneuver from the exit lane to the through lane. When the distance between the first

vehicle and the following vehicle is too short for the lane change maneuver, the following vehicle would have to slow down or swerve to avoid a crash.

Diverging is also caused by a vehicle on the through lane weaving into the left-side exit lane. It often occurs when drivers assume that the off-ramps are located on the right side. Weaving is caused by an exit vehicle slowing down on an optional lane. This type of conflict occurs between two adjacent vehicles traveling on the same lane. When the first vehicle is diverging from the original direction, it might slow down to make the necessary maneuver. If the following distance was too close, weaving would occur.
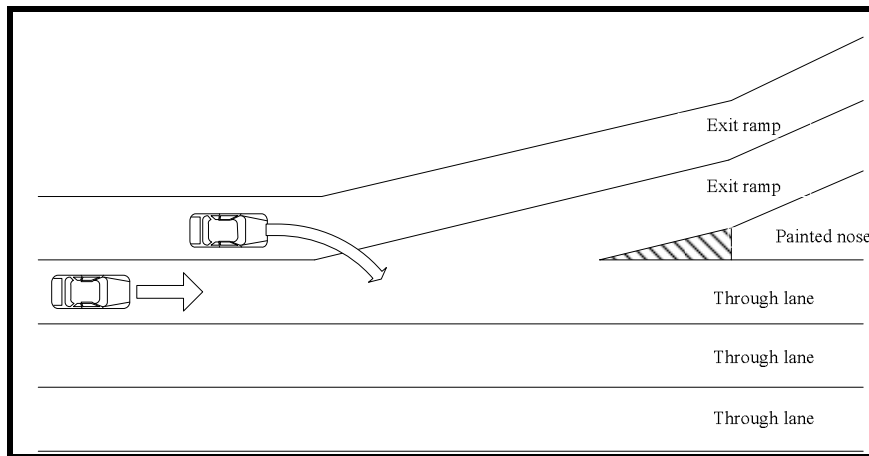
Figure 6 Merging from Exit Lane to Through Lane on Left-Side Off-Ramp
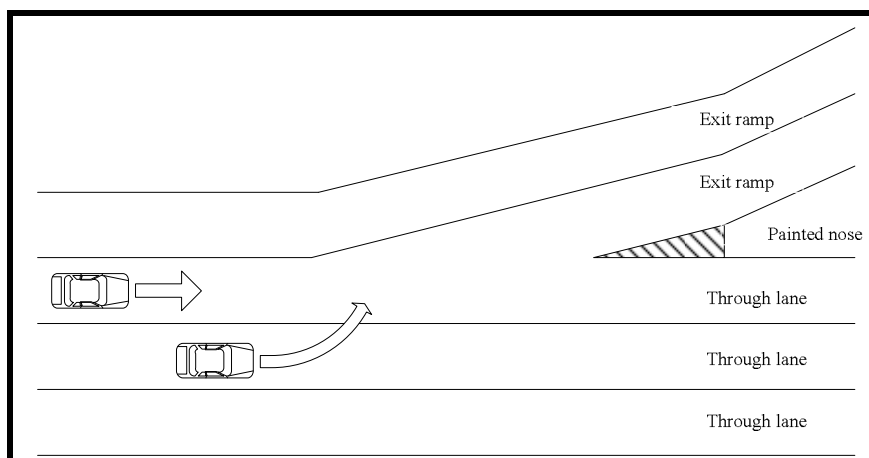
Figure 7 Diverging from Through Lane to Exit Lane on Left-Side Off-Ramp

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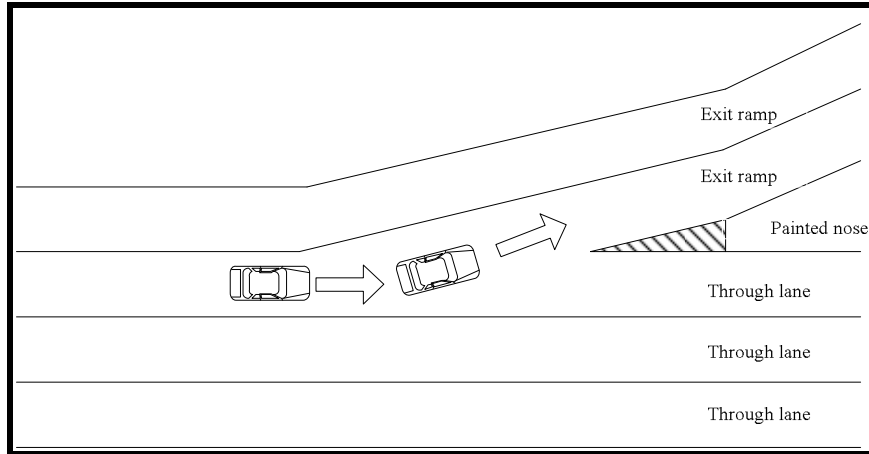
Figure 8 Weaving between Exit and Following Vehicles on Left-Side Off-Ramp

The most dangerous conflict is called "aggressive lane change" or "last second lane change", which is plotted in Figure 9. In the field, it was observed that some drivers parked their cars at the painted gore area to avoid exiting the freeway from the left-side exit lane, and then waited for a suitable gap to merge back into the freeway. Due to not having an acceleration lane, the reentry speed for the vehicles parking at the gore area is very low and this might cause severe rear end collisions and conflicts with other vehicles at a high speed.
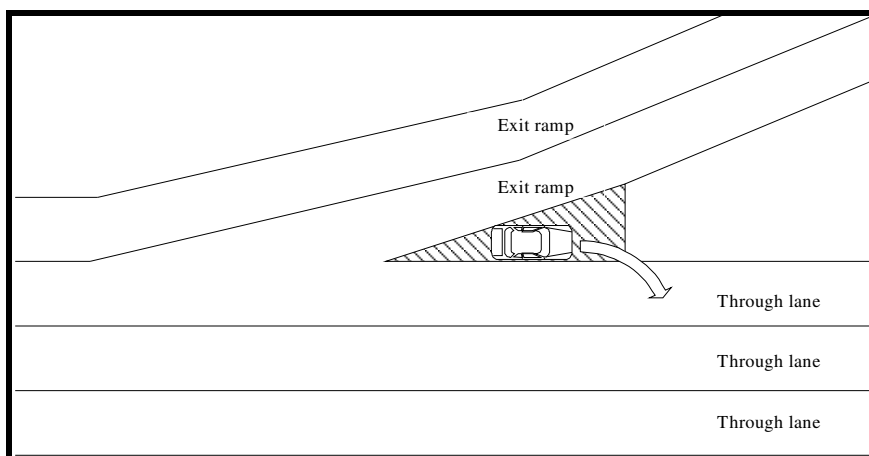
Figure 9 Crossing of Aggressive Vehicle on Left-Side Off-Ramp

The left-side off-ramps are not frequent on most interstate highways, and their impacts on freeway safety are not really clear. This study would examine the two most widely designs left-side off-ramp in Florida, which is Type I - one left-side exit-lanes and Type II - two left-side exit-lanes with an optional lane. Type I is comparable to Type 1 design type and Type II is comparable to Type 3 design type on the right-side freeway diverge section. For convenience, Type 1 and Type 3 are named as Type I* and Type II* corresponding to the left-side off-ramps. The four design types are shown in Figure 10.

1.4.2 Entire Exit Ramp Sections

The entire exit ramp section is defined as the beginning of pointed nose to the end of ramp terminal. Many possible influential factors might affect ramp designs. These factors may include but not limit to ramp configurations, ramp design speed, number of exiting lanes, ramp terminal control types, ramp length, ramp curvatures, etc.

Ramp configurations are generally considered as the ramp types in the previous studies. Bauer and Harwood's (3) study showed 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 features, the ramp configuration was considered as the ramp type in this study. Four widely used configurations in Florida are identified. They were briefly defined as diamond exit ramps, out connection exit ramps, free-flow loop exit ramps and parclo loop exit ramps. Figure 11 exhibits the four ramp configurations by the shape of ramps in the simplified mode.

Study Area

Upstream 1500 ft | Diverge Area | Downstream 1000 ft

Lane 3-Through Lane

Lane 2-Through Lane

Lane 1-Through Lane

Deceleration Lane

Type I* (Type 1) One-Lane Right-Side Off-Ramp

Study Area

Upstream 1500 ft | Diverge Area | Downstream 1000 ft

Deceleration Lane

Lane 3-Through Lane

Lane 2-Through Lane

Lane 1-Through Lane

Type I One-Lane Left-Side Off-Ramp

Study Area

Upstream 1500 ft | Diverge Area | Downstream 1000 ft

Lane 3- Through Lane

Lane 2-Optional Lane

Lane 1-Drop Lane

Type II* (Type 3) Two-Lane Right-Side Off-Ramp

Study Area

Upstream 1500 ft | Diverge Area | Downstream 1000 ft

Lane 3- Drop Lane

Lane 2-Optional Lane

Lane 1-Through Lane

Type II Two-Lane Left-Side Off-Ramp

Figure 10 Two Left-Side Off-Ramp Types Comparable to Right-Side Off-Ramp Types at Freeway Diverge Areas

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Figure 11 shows a diamond exit ramp which is a one-way road with both left and right turns at terminals, an out connection exit ramp which only supplies the single right turn at the ends of exit ramps, and 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.

| Diamond Exit Ramp | Outer Connection Exit Ramp |
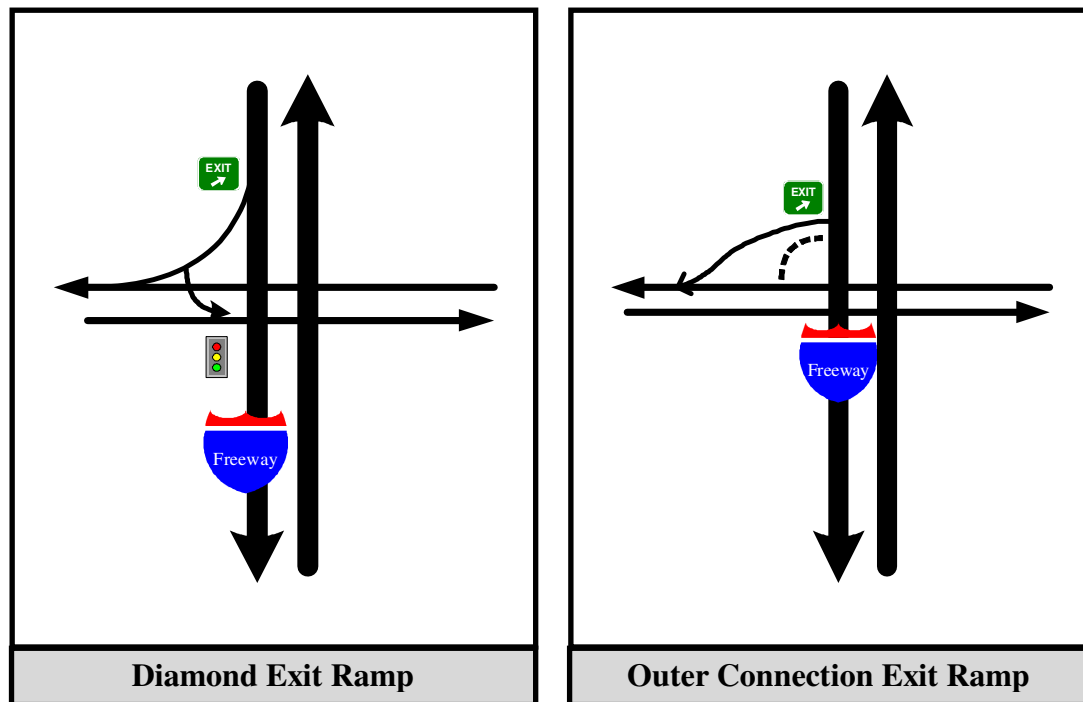
Figure 11 Typical Four Exit Ramp Configurations

| Free-flow Loop Exit Ramp | Parclo Loop Exit Ramp |
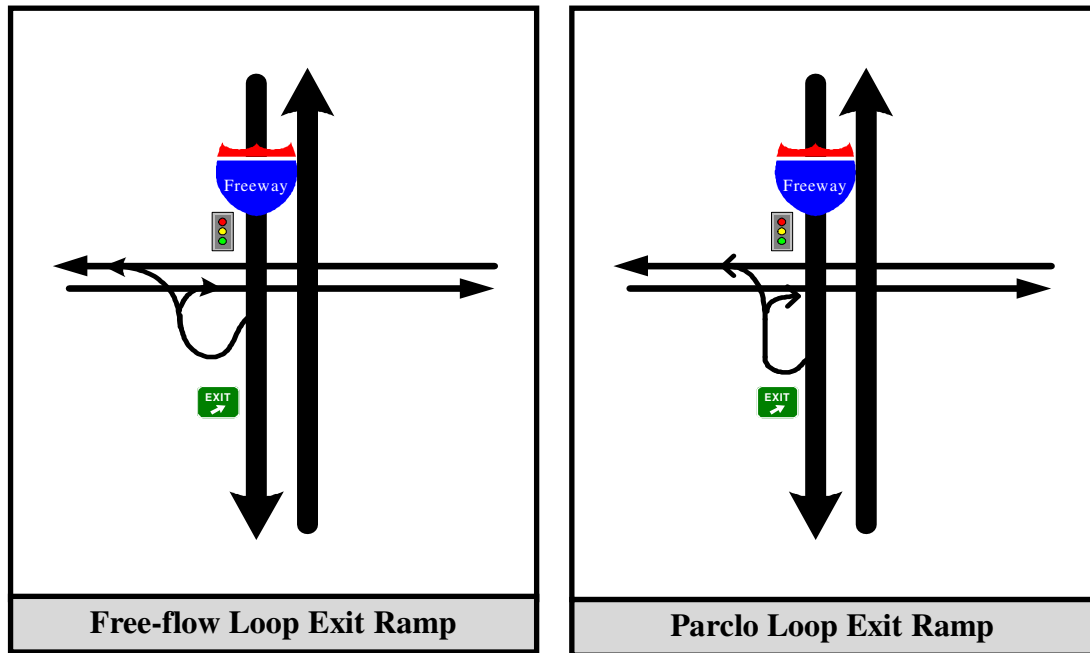
Figure 11 (Continued)

1.5 Research Approach

Previous studies were reviewed and the methodology to measure the safety performance was selected. Crash histories at selected freeway segments were collected to be further investigated. Cross-sectional comparisons were conducted to understand the safety impacts of the two segments, freeway diverge areas and exit ramp sections. On the basis of the collected crash data for the diverge areas, statistical analyses were conducted to quantitatively evaluate the impacts of different design types 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.

Detailed methodologies are discussed in Chapter 3. 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.

In order to achieve the research purposes, following tasks were made to obtain rational conclusions. Existing methods and technologies were gathered to reach the goals of the research subjects. Possible applications were identified the in the research fields. After summarizing these potential measurements, useful methods from previous studies were selected and detailed developments were conducted. 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 freeway diverge areas and exit ramp managements. In this study, four steps containing ten main tasks were categorized to organize the research procedures in an efficient way, as follows:

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, containing 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 to complete the dissertation. These four steps contained all the needed tasks for this research study and have been proved successfully in past research projects.

CHAPTER 2

LITERATURE REVIEW

Previous studies and findings regarding the safety performance of freeway diverge areas and exit ramp sections are reviewed and summarized in this chapter. Freeways are categorized as the highest functional hierarchy in the highway system. The grand reliance on this facility promotes the essence of applying a much reliable, efficient and sustainable infrastructure system, thus the safety effect is obviously an important consideration in the freeway exit ramp design. Many factors relate to the safety performance on freeways and their adjacent facilities. The wide variety of site geometric features, traffic characteristics, roadway types, or design layouts could eliminate or increase conflict points at some degrees.

This study did a comprehensive literature review, which include but not limit to the current state and national freeway and ramp management handbooks, geometric design guidelines from AASHTO (1) and Highway Capacity Manual (4), reports from National Cooperative Highway Research Program (NCHRP) and State DOT, proceedings from national and international transportation symposium, papers from referred scientific journals, etc. Current rules, regulations, standards, and practices in Florida were evaluated and summarized in the sequent sections as well.

2.1 Freeway Diverge Areas

2.1.1 Widely-Spaced Situation

Few research studies have focused on the impacts of the number of lanes used by traffic to exit freeways. The types of freeway exits were usually defined by ramp configurations such as diamond, loop, directional, outer connector, or other types instead of the lane balance theory at the diverge areas. Though several crash predictive models were developed for crash frequency by different explanatory variables such as traffic volumes, number of lanes or ramp design elements and many design handbooks and guidelines focused on the relationships between geometric elements and collision, none of these has evaluated the impacts of the combination of number and arrangement of exit lanes at this specific freeways segment.

In 1969, Cirillo et al. (5) did an innovative investigation on the factors contributing to highway crashes. They found that the relationship could be established between the number of fatal crashes and geometric parameters. The geometric factors included the interchanges types, shoulder types, sight distance, delineators, and surface types.

In 1998, Bauer and Harwood (3) explored the relationship between traffic crashes and highway geometric design elements. The statistical modeling approaches used in that research included the Poisson and negative binomial regression models. Several models were developed to predict crashes on ramp sections and speed change lanes. The variables in the crash models included the freeway average annual daily traffic (AADT), the ramp AADT, the area type (rural/urban), the ramp type (on/off), the ramp configurations, the right shoulder width, and the ramp length. Among these variables, it

was found that ramp AADT explained most of the variability in the accident data. Crash frequency increased with the increase of the ramp AADT. The crash predictive model for the deceleration lane was given by:

$$y = (X_1)^{1.04} \exp(-9.73 - 1.21X_2 + 0.09X_3) \tag{1}$$

Where y is the expected number of total crashes in a 3-year period on the deceleration lanes; X_1 denotes the ramp AADT (veh/day); X_2 is a dummy variable for area type (= 1 if the area type is rural, 0 otherwise); and X_3 denotes the right shoulder width. Other models were built to find out the functions of different variables in different kind of models. The dependent variables were the total crash counts on the speed-change lanes, on the entire ramp sections, on selected ramp sections, or on the 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 the area type, the ramp type, the ramp configurations (diamond, loop, outer connector, others), the length of speed-change lane, and the entire ramp length. Another main finding was that models for the total crashes achieved much better results than those for the only fatal and injury crashes. The models also combined the overall crashes happening on on-ramps and off ramps, and those on acceleration lanes and decelerations lanes. It was found that more crashes usually occurred on off ramps than on ramps.

In addition, the design requirements for acceleration lanes and deceleration lanes vary such as the ramp length, the curvature, and the design speed. So ramp configurations could not be defined as the ramp types at the freeway diverge areas. Without judging these factors, study results would decrease the accuracy of the conclusions, narrow the

applications of the results and may not disclose the existent situations. This study would provide reasonable methods which have been proved strappingly employed in the safety studies.

Bared et al. (6) developed a model to estimate the crash frequency for entire ramps as a function of the ramp AADT, the freeway AADT, the deceleration lane length and the ramp configuration. The focus of that study is on the safety effects by the acceleration and deceleration lanes lengths. The ramp configuration was considered in that study, including diamond, parclo loop, free-flow loop, and outer connecter. The model shows that ramps crash frequency increases with the increase of the ramp and freeway AADT and decreases with the increase of the deceleration lane length. Sensitivity analysis results show that a 100 ft increase in deceleration lane length would result in a 4.8% reduction in crash frequency. The final crash prediction model is given as follows:

$$N = (RAADT)^{0.78}(FAADT)^{0.13}Exp(-7.27 + 0.45DIA + 0.78PAR - 0.02FF \\ + 0.69OC - 0.37RUR + 0.37DECEL - 2.59SCLEN + 1.62RLEN) \tag{2}$$

Where N is the expected number of total accidents in a three-year period on the ramps combined with speed-change lanes; RAADT denotes the ramp AADT (veh/day); FAADT is the freeway AADT in the direction where the ramp is located (veh/day). DIA, PAR and FF are dummy variables defined for diamond ramp, parclo loop ramp, and free-flow ramp respectively; DECEL is the dummy variable for off/on ramp (=1 if the ramp is an off ramp, 0 otherwise); SCLEN denotes the speed change lane length (miles) and RLEN is the ramp length (miles).

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 of the optimal ramp designs. The newest instruction for the ramp designs is the ITE "Freeway and Interchange Geometric Design Handbook" edited by Joel (8) 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 it is valued as an accompaniment of the AASHTO (1), the Highway Capacity Manual (HCM) (4), and Traffic engineering Handbook 5th Edition (9).

In order to achieve a safe, efficient and sustainable highway system, Highway Safety Improvement Program (HSIP) (10), established by Federal Highway Administration (FHWA), was signed into law on the year of 2005. It is acting as a core-Federal aid program. The overall purpose of the program is to help states decrease the number of crashes and provide optimal ways for arranging, applying, and estimating safety plans. From side to side of this program, all associated issues to improve highway safety should be recognized, measured, and evaluated during highway planning, designs, constructions, and maintenances. The program also mentioned that previous methods such as regression models or statistical tests that have been proved as useful methods in the safety studies. The next paragraph summarizes the wide applications of these methods.

Sarhan et al. (11) developed the approach to help achieve the optimal crash predictive models. The expected collision frequency was found related to the acceleration and deceleration lanes lengths. Garcia et al. (12) analyzed different deceleration lengths as functions of exit trajectory types, speeds, and localizations. Joanne and Sayed (13) undertook the study to quantify the relationship between the design consistencies on the roadway and safety performance. The generalized linear regression was used as a

quantitative tool to evaluate the impact of design consistency on road safety. Munoz and Daganzo (14) predicted the queued length at a wave speed about 13 mph during congested traffic conditions by applying KW model. This method is widely used in the safety evaluation of intersections as well as freeway sections. Maze et al. (15) analyzed the crash rates, crash severity rates and fatal crash rates at TWSC expressway intersections by Poisson regression models.

Keller et al. (16) divided crashes by different collision types such as angle, left-turn, head-on, rear-end and pedestrian/bicycle by linear regression models. The speed limits were found to be significant for these crash models. Bernhard et al. (17) estimated the benefits of assigning improvement at different crash locations by severity. Hypothesis tests were conducted by using normal distribution with high number of crashes and by using Poisson distribution with a low number of crashes. The statistical tests were usually employed to identify some hazardous sites with high crash-prone locations at some particular level of confidence. In fact, the level of confidence is that 100% minus the Type I error of the hypothesis tests. Type I error is the percentage that the sites was misidentified as the hazardous site. They concluded that the program would benefit to public traffic to make the possible efforts to improve the safety studies.

Other studies focused on revealing the geometric, traffic, or other influential factors on the freeway mainline sections. Rakha and Zhang (18) modeled the traffic volume on a total of 34 different weaving sections including merge and diverge areas with appropriate boundaries. The paper demonstrated that the volume estimated by the model had a significant effect on drivers' behavior on the weaving sections. Abdel-Aty et al. (19) tested various speed limits to evaluate the safety improvement on a section of

Interstate 4 (I-4) in Orlando, FL. Real-time crash likelihood was calculated based on split models to predict 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 of the diverge areas should be large in magnitude (15 mph) and implemented within short distances (2 miles). It makes obvious that speed limit have some specific effects on the collisions from the upstream to downstream of freeways diverge areas.

Cassidy et al. (20) noticed the problem that queuing from the segment's off-ramp spilling over and occupying its mandatory exit lane came up frequently. The situation delayed the mainline vehicles as well and would increase weaving conflicts. Janson (21) examined the relationship between ramp design parameters 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 for each exit 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 general 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 so that the crash data have the specific feats.

One research study, concerning on the number of lanes used by traffic exiting freeways, was conducted by Batenhorst and Gerken (22). 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) (23), CORridor-microscopic SIMulation program (CORSIM) (24) and Simtraffic (25), to analyze the operational conditions at weaving area on twenty locations by measuring the Level-Of-Service (LOS). The range of traffic and geometric conditions among the twenty sites varied. The findings of the case study suggested 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 designing efficient freeway facilities and to help researchers understanding the operational effects of different design types. Even though this study considered exit lane numbers at the freeway diverge areas, the better LOS could not necessarily stand for better safety performance, and these two might have opposite results in some cases.

In summary, the impacts of different design types on the safety performance at widely-spaced freeway diverge areas have not been well studied or documented until recently. Several previous studies have evaluated the different ramp configurations such as diamond, loop, directional, outer connector, and other on the safety performance; however, these studies have not considered the lane balanced issues or basic number of lanes at the diverge areas. It is urgent, necessary and beneficial to conduct the safety evaluation at this specific area.

2.1.2 Closely-Spaced Situation

While the distance between an entrance ramp and an exit ramp is closed, the entering traffic will merge to the left to join the approaching traffic, while the exiting traffic will merge to the right to exit the freeway. The presence of approaching freeway

vehicles, merging vehicles and diverging vehicles within a relatively short freeway segment creates more complicated driving environments as compared to the widely-spaced situation. In past years, some studies have examined the safety and operational performance of freeway entrance and exit ramps (5, 6, 21, 26, 27, and 28). The focuses of these studies were on the safety impacts of various design elements associated with entrance and exit ramps, such as the ramp configurations and the length of the deceleration lanes, etc. Relative fewer studies are available regarding the safety and operational impacts of the lane arrangements on freeway mainlines under the closely-spaced situation.

Several studies have examined the operational performance of the weaving segments between entrance and exit ramps. In the current edition of HCM (4), a procedure is provided to determine the capacity of the weaving segments between entrance and exit ramps. In addition, Batenhorst and Gerken (22) studied the operational effects of the weaving areas created by auxiliary lanes between two successive interchanges. Two situations were considered in that study: 1) the auxiliary lane was terminated at a one-lane exit ramp; and 2) the auxiliary lane was terminated at a two-lane exit ramp. Based on the traffic simulation results at twenty locations, Batenhorst and Gerken compared the operational effects of these two lane arrangements. It was found that the two-lane exit ramp resulted in higher total system delay than a one-lane exit ramp; and the increase in total system delay ranged from 0.4% to 309.9% with an averaged 33.7%. It indicated that the complex traffic situations occur in this area.

Abdel-Aty and Huang (29) 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 the presence of 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. So the result was a little count-intuitive that different design features on diverge areas would have an effect on familiar drivers as well as on the unfamiliar travelers.

At present, little documentation is available regarding the safety performance of the freeway segments with closely spaced ramps, and no widely accepted guidelines is available regarding the coordination of lane balance and basic number of lanes for this particular situation. To understand the different design types of basic number of lanes and lane balance affect safety at closely-spaced freeway diverge areas, following two questions remained to be answered in this study: 1) what is the safety performance of different design types at the closely-spaced freeway diverge areas?; and 2) what are the contributing factors and how can they affect the crashes occurring at closely-spaced freeway diverge areas?

2.1.3   Left-Side Off-Ramp

To examine the impact of ramp locations at freeway diverge areas on traffic safety, the newest instruction for ramp design is the "Freeway and Interchange Geometric Design Handbook" edited by Joel (8), published by the Institute of Transportation Engineers (ITE) in 2006. The handbook focuses on geometric and operational characteristics of freeways and interchanges, including both on-ramps and off-ramps. It

recognizes that geometric design procedures for freeways and interchanges may vary. It is valued as a supplement of the AASHTO (1), the Highway Capacity Manual (HCM) (4), and Traffic engineering Handbook 5th Edition (9).

A few studies were found to examine the factors that affect freeway off-ramp safety. However, no impact of left-side off-ramps on traffic safety was included in these studies. McCartt et al. (30) examined 1,150 crashes that occurred on heavily traveled urban interstate ramps in Northern Virginia. About half of all these crashes occurred when at-fault drivers were in the process of exiting interstates, and the crash type most frequently associating with exiting ramp was the run-off-road crash. It was also found that the run-off-road crash frequently occurred when vehicles were exiting interstates at night, in bad weather, or on curved portions of ramps.

To identify the best design for a guide sign for the two-lane exit with an option lane, Upchurch et al. (31) examined the different off-ramp designs. Four candidate sign designs were evaluated using 96 test subjects in a driving simulator. The number of missed exits and the number of unnecessary lane changes were adopted as the measures of effectiveness (MOE). One design was recommended to be included in the Manual on Uniform Traffic Control Devices (MUTCD) (32) as a signing guideline for a two-lane exit with an optional lane. However, only off-ramps on the right sides were considered in this study.

After closely reviewing the literature, currently no conclusions on the safety performance of left-side off-ramps at freeway diverge areas has been made. The left-side off-ramps are not as normal as right-side off-ramps on most interstate highways, and their impacts on the freeway safety are not clear. As a result, one purpose of this study is to

evaluate the safety performance of left-side off-ramps comparing to similar right-side off-ramps and identify the contributing factors to crashes at selected freeway segments.

2.2   Exit Ramp Section

The entire exit ramp section is another important component in the highway facility. Ramps are all one-way roads with one or more legs at terminals connecting secondary crossroads. The variety of design speeds, configurations, speed differences among freeway and ramp section, ramp lengths or the direct connection features determine dissimilar effects on safety. Following subsection described the previous study results regarding the safety performance on the exit ramp sections.

Lord and Bonneson (26) 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 ramp types. Bauer and Harwood (3) applied the Negative Binomial (NB) regression model to predict total crashes on the entire ramp section. The study concluded that diamond ramp have slight less crash frequency than other ramp types under the same geometric and traffic condition.

Later, Khorashadi (27) used another method, ANOVA test, to forecast the relationship between crash frequencies and ramp configurations and geometry parameters. It was found that the geometric elements had much weaker impacts than the ramp configurations. McCartt et al. (30) examined 1,150 crashes occurring on heavily traveled urban interstate ramps in Northern Virginia. The three major common crash types, run-

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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.

Hunter et al. (33) conducted field observations on operating speeds between ramps and freeways by videotaping. Notable conclusions were drawn that vehicle speeds on exit ramps were much higher than the suggested speed limit. Large difference was observed between the ramp suggested speed and the field operating speed. Some unfamiliar drivers slowed down the speed approaching the exit ramp while some familiar drivers still travelled at a high speed which is relative far above the suggested speed. That might be a vital reason why rear-end crashes account a large percent of crashes on the exit ramp sections.

Some researches focused on the effects of different factors on the ramp sections on the traffic safety. These studies comprised Newell's (34) "Delays caused by a queue at a freeway exit ramp", Shaw and Mcshane's (35) "Optimal Ramp Control for Incident Response", and Hunter et al.'s (36) "Summary Report of Reevaluation of Ramp Design Speed Criteria". Newell clarified that the graphical solution was 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 the freeway speed limit. This conclusion accommodated to Hunter et al.'s (33) result that operating speed on the exit ramp was higher than the design speed on the exit ramp.

It is obvious that many studies used ramp configurations as ramp types to compare the safety performance. The conclusions included free-flow ramps had more potential crashes than other types; increasing ramp volume might increase potential crashes; the post speed limit on the ramp had some impacts on both local/familiar drivers and unfamiliar drivers; and the operating speed was usually much higher than the suggested speed.

Even several useful results were made on the exit ramp sections; none of these studies was conducted in Florida. In addition, few considered the following two issues in the safety issues, ramp terminal treatments and ramp lane changing named widening on the exit ramp segment. The definition of ramp terminal treatments in "Ramp Management and Control Handbook" (2) is that 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 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, the signal timing improvements, the ramp channelization, the geometric improvements, and the signing or pavement marking 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 other geometric deficiencies. Signing and pavement marking improvements deal with guiding motorists of downward conditions and facilitating vehicle movements.

Implementations of ramp terminal treatments could reduce delay and queuing length, decrease conflict points, enhance safety and minimize the impact both on upstream and downstream highways and arterials. The functions vary by the 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 ramp sections if the ramp length is not long enough. Retting et al. (37) 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 countermeasures to enhance safety in general solutions.

This study would consider the terminal control methods to expose their impacts on safety. One study conducted by Bared et al. (28) compared crashes between single point and tight diamond ramps related crashes on cross roads only. Single point diamond interchange is diamond ramp free-connects to the cross roads and 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 and a Negative Binomial model to predict total crashes on the exit ramp and cross-road flow was built. However, the safety comparison did not show a significant difference between the two types of terminals. This study only compared one terminal treatment as ramp channelization; however the sites number here was not sufficient enough to do a regression model.

The lanes widening is one of the efficient strategies to manage ramp flow. Widening in this study is defined as the number of lanes changing after the pointed nose or in the middle of the entire ramp. From the field observation and site photos, several ramps have widened lanes after the pointed noses. As a result, this study would consider this factor to see whether this strategy would influent the safety performance of exit ramps.

CHAPTER 3

METHODOLOGY

This chapter describes the selected methodologies which have been applied to this study. The principles for selecting the main methods include what the functions are, whether they are practical or easily applied to the data base, and how the potential results are useful in the traffic engineering. The research subjects included two main parts, freeway diverge areas and exit ramp sections. After reviewing prior studies, guidelines, handbooks and related researches, useful methodologies and important parameters were identified for the safety analysis. The main approaches used included the cross-sectional comparison method, hypothesis tests, and generalized regression models. Based on the crash data gathered at selected freeway segments, cross-sectional comparison were conducted to quantitatively evaluate the safety impacts of different design types. Crash frequency, crash rate, crash severity, and crash types were compared associated with different design types at freeway diverge areas and exit ramp sections respectively.

The statistical methods used in this study include 1) Hypothesis test (t-test or Z-test): used for comparing average crash frequency and crash rate between different design types; 2) Proportionality test: used for comparing target crash types and crash severity between different design types; and 3) Generalized regression models: developed for identifying and quantifying the factors that contribute to the crashes at selected freeway areas, (widely-spaced, closely-spaced, and left-side off-ramps) and exit ramp sections.

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3.1 Crash Frequency and Crash Rate

Crash frequencies and crash rates are two indicators that are generally used in the safety studies to compare different treatments or groups. This research project would calculate the two indicators by each design types for further analysis.

3.1.1 Crash Frequency

The crash frequency is the real number of crashes happening at a certain location or segment in a particular time or time interval. It is commonly used since it has several benefits. Firstly, the crash data are easy to get and simple to calculate. Secondly, the meaning behind is straightforward so that governmental officials, engineers, and publics could understand it readily. The third virtue is that it could represent diverse places in one parameter and could change directly while the selected lengths or vicinity of the segments changed. The resource of the noticed crashes for this study is only from police long form crash report which describes specific features for each crash. Florida Traffic Crash Annual Report (CAR System) provides detailed crashes and updates the database each year.

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

$$C \ = \ \frac{\sum_{i=1}^{n} c_i}{N} \tag{3}$$

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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 widely-spaced freeway diverge areas, four design types, Type 1, Type 2, Type 3, and Type 4, were classified so that four groups were chosen to compare the mean values of crash frequency. In the closely-spaced situation, three types, Type A, Type B, Type C, were compared. In addition, the average crash number of two types on left-side off-ramp and similar right-side off-ramps on freeway diverge areas were compared. On the exit ramp sections, four exit ramp types defined before were analyzed as well. 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 statistical indicators, the mean value, the median value, the maximal and minimal values, are calculated respectively to represent the crash distribution.

3.1.2 Crash Rate

In this study, the crash rate is defined as crashes per million vehicles per vehicle miles traveled on a specific section. The crash rate is used as a truthful criterion for

segments under the same geometric and traffic conditions to narrow the impacts of the important factors. The crash rate, r for a particular freeway segment can be calculated in the following formula:

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

(4)

Where,

r = defined crash rate (crashes per million vehicles per mile);

A = number of report crashes (crashes),

T = number of years;

V = average daily traffic volume (veh/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 when other factors remain same. The corresponding ADT for each site was obtained from annual Florida traffic information CDs. The time frame was determined when site characters have not been changed in continuous time periods. At freeway diverge areas, another type of crash rate is defined by joint consideration of both freeway AADT and exit ramp AADT to minimize the impact of AADT, denoted as:

$$r_i^{'} = \frac{1,000,000 \times A}{365 \times T \times V^{'} \times L}$$

(5)

Where,

$V^{'} = \sqrt{\text{AADT}_{\text{freeway}} \times \text{AADT}_{\text{ramp}}}$) (veh/day);

$AADT_{freeway}$ = freeway AADT (veh/day);

$AADT_{freeway}$ = exit ramp AADT (veh/day).

The average crash rates are the arithmetic means of crash rates. The statistical assumption is similar to the average number of crash as mentioned before. The average crash rate, R, is defined as:

$$R \ = \ \frac{\sum\limits_{i=1}^{n} r_i}{N} \tag{6}$$

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 crash rate distributions.

3.2 Crash Type and Crash Severity

In order to estimate the safety performances at freeway diverge areas and on the exit ramp sections, crash types and crash severity were also compared by the percentages to the total number of crashes. Crash type and crash severity are widely used in the safety analysis to explore the crash characteristics.

3.2.1 Crash Type

In the crash database maintained by Florida Department of Transportation (DOT), the crash type is defined by the first harmful event of at-fault vehicles. The comparison of crash types can help identify driver behaviors which are probably related to the design

types. A total number of 40 crash types are contained in the Florida's CAR system. The three most common crash types occurring at diverge areas and exit ramps are the rear-end crash, the side-swipe crash and the angle crash. Thus, the three crash types are defined as the target crash types in this study.

Rear-end crashes regularly takes 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 this crash type can range from minor to severe depending on the speed of the following vehicle that hits the first vehicle.

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

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. Angle crashes usually cause severe crashes as compared to rear-end crashes. The three types mentioned above are the most concerned types at the selected freeway areas.

3.2.2 Crash Severity

Crash severity level is recorded for each police reported crash. Three major levels of crash severity generally defined can be classified to three categories:

1) Property-damage-only (PDO) crashes;

2) Injury crashes;

3) Fatal crashes;

For a property-damage-only crash, only properties are damaged but no person is hurt. For an injury crash, at least one person is lightly hurt because of the crash. For a fatal crash, at least one person is dead within 90 days after the crash. In this study, the crash severity was categorized into two levels, PDO crashes only and injury/fatal crashes.

3.3 Cross-sectional Comparison Approach

The method of cross-sectional comparison is satisfactory to provide adequate and reasonable consequences. It is long believed that cross-sectional approach is a logical and efficient technique to judge the safety effects. The cross-sectional method has been proved valuable and has been performed on a number of past studies, including median alternatives, right turns followed by u-turn to direct left turns and truck accidents at freeway ramps (21).

In the transportation field, traffic engineers have experimental judgments for most influential factors, for example, the section length, average daily traffic (ADT), the speed, or the ramp length. Cross-sectional analyses to evaluate different treatments are fairly reliable for the results. Briefly, reliable conclusions could be obtained within this method. In other words, it 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 by comparing crash histories of different design types.

In this study, the cross-sectional comparison were conducted to measure freeway diverge areas under different conditions by various design types and exit ramp sections by four configurations. This approach involved comparing the crash frequency, the crash rate, the target crash type, and the crash severity of a group with a treatment, to that of a

group of with another treatment. On the basis of the collected crash data, statistical analysis was conducted to quantitatively evaluate the safety impacts of different types.

The major assumption behind this comparison was that all other characteristics in the selected sites remained the same during the study period except the interested factors. The geometric factors considered in this study included the deceleration length, the ramp length, the average daily traffic (ADT), the speed limit on freeways and exit ramps, number of lanes on freeways, surface conditions, shoulder conditions and etc. By comparing crash history using statistical tests, conclusions could be reached regarding the relative safest design type among design types.

3.4 Hypothesis 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 differences in a statistical term. Observing sample data were calculated in the hypothesis tests to measure the suppositions whether they are under similar features. If the results did not support some specific assumptions, then the assumed suppositions are considered doubtful. The formula of hypothesis test 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 based on the statistical distributions including Z, t, F or χ^2 distributions. The decision of whether rejecting the null hypothesis or failing to reject is based on the statistic value ranging on the statistical distribution at a specific significant level α. Typically the level of confidence as 1-α is applied to determine the statistical range instead of α. The procedures of conducting a hypothesis test are summarized in four steps as follows:

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

   Select the Alternative Hypothesis - H_a ;

2) Step 2: Determine the level of confidence (1- α)*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 two proportions.

3.4.1 Hypothesis Test on the Equality of Two Means

Mean values of two different populations were tested to get conclusions whether to reject or fail to reject the null hypothesis. The average crash numbers and rash rates from one group to another group were be examined if they are significantly different. t-test has been widely used to test the population mean with unknown variance. It can be used to test if the difference between two population means is statistically significantly. Assumed that two populations say X_1 and X_2, where X_1 has a mean μ_1 and unknown

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variance σ_1^2 and X_2 has a mean μ_2 and unknown variance σ_2^2. The purpose is to test whether the two populations have the same mean μ_1 and μ_2. The first step is to build the null hypothesis H_0 and an alternative hypothesis H_a:

$$H_0 : \mu_1 = \mu_2 \tag{7}$$

$$H_a : \mu_1 \neq \mu_2 \tag{8}$$

The procedure is based on the fact that the difference in the sample mean, X1, X2, of two populations of interest with a sample size of n_1 and a sample size of n_2 separately, $\bar{X}_1 - \bar{X}_2$ fit the normal distribution of:

$$\bar{X}_1 - \bar{X}_2 \sim N\ (\mu_1 - \mu_2, \sigma_1^2 /n_1 + \sigma_2^2 /n_2) \tag{9}$$

The second step is to choose the level of confidence. In this study 90% is used and α equals 10%. The third step is to calculate the statistical value t_0:

$$t_0 = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}}} \tag{10}$$

with degrees of freedom given by:

$$df = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{\dfrac{(s_1^2/n_1)^2}{n_1-1} + \dfrac{(s_2^2/n_2)^2}{n_2-1}} \tag{11}$$

The corresponding p-value of the test is given by:

$$p - \text{value} = \Pr(|t| \geq \frac{|\bar{X}_2 - \bar{X}_1|}{\sqrt{\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}}}) \tag{12}$$

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

$$t_0 > t_{\alpha/2} \text{ or } t_0 < t_{\alpha/2} \tag{13}$$

As the variance σ^2 is unknown and unequal, the sample variances of $\bar{X}_1, \bar{X}_2$ can be calculated as follows:

$$S_1^2 \cong \frac{\sum_{i=1}^{n} (X_i - \bar{X_1})}{n_1 - 1} \tag{14}$$

$$S_2^2 \cong \frac{\sum_{i=1}^{n} (X_i - \bar{X_2})}{n_2 - 1} \tag{15}$$

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:

$$t_0 = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_p^2 (\frac{1}{n_1} + \frac{1}{n_2})}} \tag{16}$$

$$S_p^2 \equiv \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{17}$$

3.4.2 Hypotheses Test on the Equality of Two Proportions

On the basis of the collected crash data, statistical analysis was conducted to quantitatively evaluate the target crash types and crash severity by defined design types.

The proportionality hypothesis test was utilized in this study at freeway diverge areas and on the exit ramp 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:

$$H_0: p_1 = p_2 \qquad (18)$$

Versus

$$H_a: p_1 \neq p_2 \qquad (19)$$

H_0 can be rejected if:

$$Z = \frac{|p_2 - p_1|}{\sqrt{\dfrac{p_2(1-p_2)}{m} + \dfrac{p_1(1-p_1)}{n}}} \geq Z_{\alpha/2} \qquad (20)$$

3.5 Statistical Predictive Model

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

Generalized linear models have been widely used for modeling crashes in the safety studies (3, 6, 11, 12, 13, 14, 15, 16, and 17). 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 suggested the use of Poisson models or Negative-Binomial (NB) models for modeling the crash frequency (3, 6). 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:

$$p(Y_i = y_i) = p(y_i) = \frac{\mu_i^{y_i} e^{-\mu}}{y_i!} \ , \text{i} = 1, 2, 3, \ldots\ldots, \text{n} \tag{21}$$

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 μ to a linear predictor η. 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:

$$\mu_i = \exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik}) \tag{22}$$

Where,

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

$x_{i1}, x_{i2}, \ldots \ldots 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:

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$$\mu_i = \beta_0 x_{i1}^{\beta_1} x_{i2}^{\beta_2} \dots x_{ik}^{\beta_k} \tag{23}$$

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:

$$p(Y_i = y_i) = \frac{\Gamma(y_i + a^{-1})}{y!\Gamma(a^{-1})} \left(\frac{a\mu_i}{1 + a\mu_i} \right)^{y_i} \left(\frac{1}{1 + a\mu_i} \right)^{a^{-1}}, \; i = 1, 2, 3 \dots n \tag{24}$$

Where

y_i = the crash count at segment i,

μ_i = the expected number of crashes for segment i,

α = the dispersion parameter.

The dispersion parameter determines the variance of the Poisson-gamma distribution. Usually α 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 χ^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. If the values of both SD and Pearson's χ^2 statistic are close to (N-P), it can be taken as an indication that the model is adequately fitted (40).

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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:

$$SD = -2(\log(L_\beta) - \log(L_s))$$
(25)

Where

L_s = the likelihood under the maximum model;

L_β = the likelihood under the reduced model.

And the Pearson's χ^2 statistic can be calculated as:

$$Pearson's\chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - \mu_i}{\sigma_i} \right)^2$$
(26)

Where

y_i = the crash count at segment i,

μ_i = the expected number of crashes for segment i;

σ_i = the estimation error for segment i.

CHAPTER 4

DATA COLLECTION

This chapter describes the data collection and reduction procedures. Both freeway diverge areas and exit ramp sections were collected for further analysis. The criteria of classifying selected sites and the definitions of segment lengths are explained in this chapter. Detailed methods of identifying road sections in FDOT's system, subtracting specific site database, and tackling with the crash data for each site are illustrated in this chapter as well. The freeway diverge areas include three situations, the widely-spaced situation, the closely-spaced situation and the left-side off-ramp.

4.1 Site Selection Criteria

The study is to evaluate on the safety performance of freeway diverge areas and on exit ramp sections. In order to obtain reasonable results, criteria to identify the site segments are especially important in order to narrow the unstable and unrelated factors. The following criteria were considered for the site selection:

1) All the sites locate at the freeway mainline areas or the freeway exit ramp sections;

2) The definition of freeways in this study are the highway segments with the highest level of service and full control of accesses;

3) At the freeway diverge area, a sufficient and significant curb, bar, or other facilities in the median should separate two directions;

4) The shoulder of freeways and exit ramps should be clear, no sight obstruction, and no dangerous facilities;

5) The through lanes at freeway diverge areas should not contain large grade variations;

6) The freeway segments should be homogeneous segments without large horizontal or vertical curves because this research study want to narrow the other parameters not compared;

7) All sites are selected from Florida Highway System, including District one to District seven plus an additional Florida Turnpikes generally named as District eight;

Since different subjects are studied in this study, special requirements for each segment must be met as well. If it is a widely-spaced freeway diverge area, additional criteria are listed as follows:

8) The minimal speed limit on the freeway mainline section should be equal or larger than 50 mph;

9) Only right exit ramps are considered for the widely-spaced situation which means all exits should be at the right hand of the directions on freeways;

10) 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;

11) The distance from the merge point of upstream entrance to the painted nose of downstream exit is larger than 0.5 mile;

12) Deceleration lanes are measured from the beginning of the taper or widening points to the painted nose;

13) Four different design types may have different number of lanes, but the segment lengths remain same.

If it is a closely-spaced freeway diverge area, additional criteria are applied to eliminate the impacts of various external factors as follows:

14) The minimal speed limit on the freeway mainline section should be equal or larger than 50 mph;

15) The selected freeway segment should have a right entrance which is closely followed by a right exit;

16) The distance from the merge point of upstream entrance to the painted nose of downstream exit is less than 0.5 mile;

17) The impacts of left exit ramps are not incorporated for this situation;

18) The selected freeway segments should be straight segments without large horizontal or vertical curves;

19) The selected ramps under this situation should not be cloverleaf loop ramps;

If it is a left-side off-ramp at freeway diverge area, following criteria need be met:

20) The minimal speed limit on the freeway mainline section should be equal larger than 50 mph;

21) Only two types of exit ramps, two-lane exit with an operation lane and two exclusive exit lane, were selected;

22) Only left exit ramps are considered for this situation which means all exits should be at the left hand of the directions on freeways;

23) 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;

24) The distance from the merge point of upstream entrance to the painted nose of downstream exit is larger than 0.5 mile;

25) Deceleration lanes are calculated from the beginning of the taper or widening points to the painted nose;

26) The selected sites include two design types comparing to the right-side design types under the similar geometric and traffic conditions;

The exit ramp sections that connect the painted nose at freeway diverge area to the beginning of secondary roads should meet subsequent extra criteria:

27) Only right-side exit ramps are considered in the sites;

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

29) All suggested or design speed limits are larger than 25mph no matter the ramp configurations or the ramp lengths.

These criteria mentioned above ensure the candidate sites selected without low speed limits at the freeway diverge areas and no large difference of speed limits exit between the freeway mainline section and the ramp sections. This would make sure the same characters except the interesting variables for the statistical analysis. The lane width is an important parameter in this study so that the lane width is not necessarily synchronized during the sites selection procedures. From the field studies, all the preferred segments were from the interstate highway systems, expressways, turnpikes, and parkways in Florida.

4.2 Segment Length Definition

The segment lengths for four subjects are defined in the following subsections, including the widely-spaced situation, the closely-spaced situation and the left-side off-ramp at freeway diverge areas, and the exit ramp section.

4.2.1   Widely-Spaced Freeway Diverge Area Length

The freeway diverge segment under this situation 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 pained nose. Thus, the length of the freeway diverge segment in this study equals 2500 ft for each site. The definition of each design type at the widely-spaced diverge area is

given in Figure 12 through Figure 15. They include the whole study sections that combine the declaration areas and their surrounding areas.

Using different influence distances around the upstream and downstream of painted nose might result in different analysis results. If the selected influence distances are too long, crashes reported on selected freeway sections may include some mainline crashes not related to the diverge sections. If the selected influence distances are too short, however, the selected freeway segments do not cover the entire influence area of exit ramps. Though the definition of influence area reflects researchers' subjective judgments, the following facts were considered when defining the influence area:

1) The freeway segment should cover the entire freeway diverge area which includes the whole deceleration lane upstream of the painted nose. In this study, the length of deceleration lanes at selected sites range from 26 ft to 918 ft;

2) The current edition of the Manual on Uniform Traffic Control Devices (MUTCD) mandates that an interchange guide sign should be put 1320 ft upstream of the exit to supplement drivers to take proper maneuvers (32);

3) The HCM (4) suggests 1500 ft beyond the painted nose in the simulation software including CORSIM and HCS (24);

4) The field observations at 30 sites show that many drivers start lane change maneuvers when they observe the interchange guide sign;

5) To make the conclusions of this study comparable to previous studies conducted in this area, the selected influence distance should also be comparable to those used in previous studies. In previous studies, the selected influential distance located upstream of the painted nose ranged from 1000 ft to 2000 ft (6, 22, 31).

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Due to these reasons, a 1500 ft section was selected as the influential area located upstream of pained nose and 1000 ft downstream the painted nose on the freeway mainline sections.
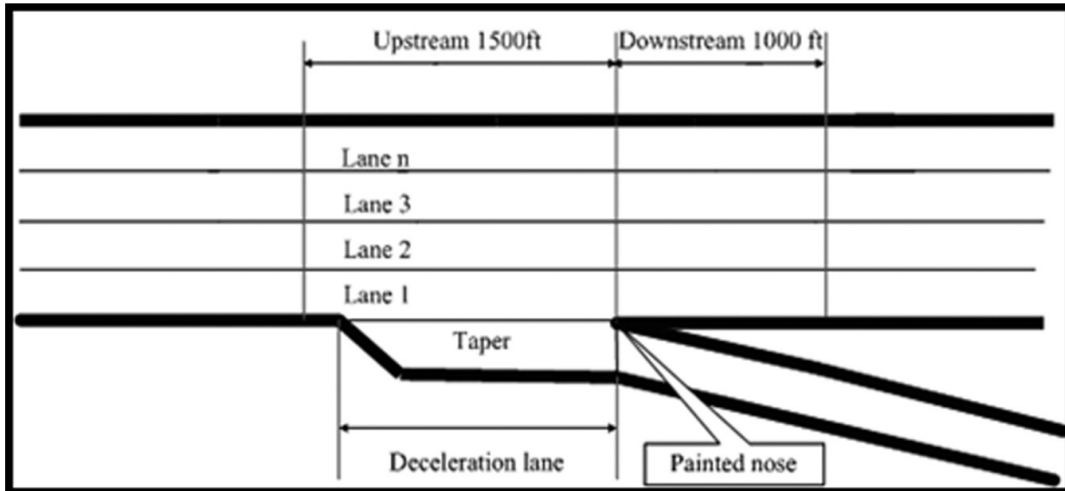
Figure 12 Segment Length for Type 1 at the Widely-Spaced Diverge Area
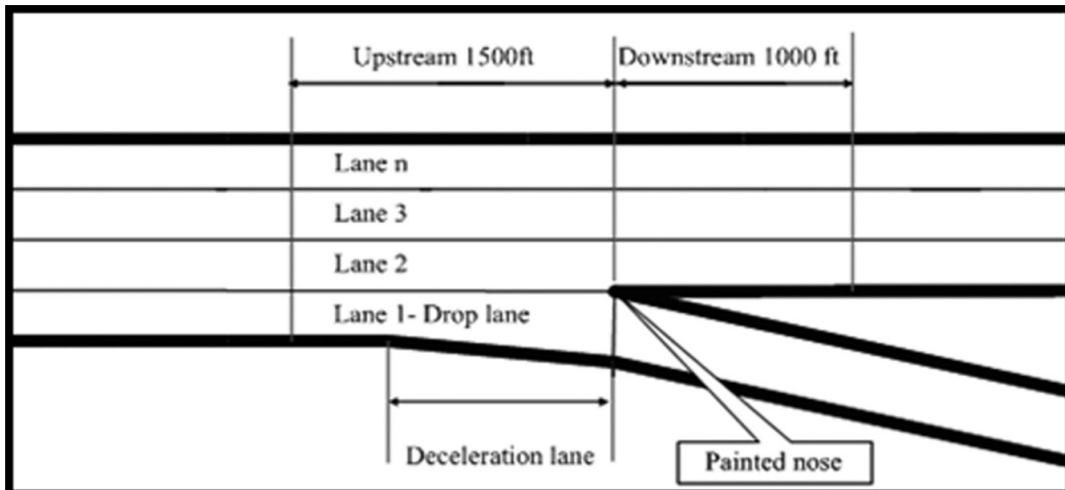
Figure 13 Segment Length for Type 2 at the Widely-Spaced Diverge Area
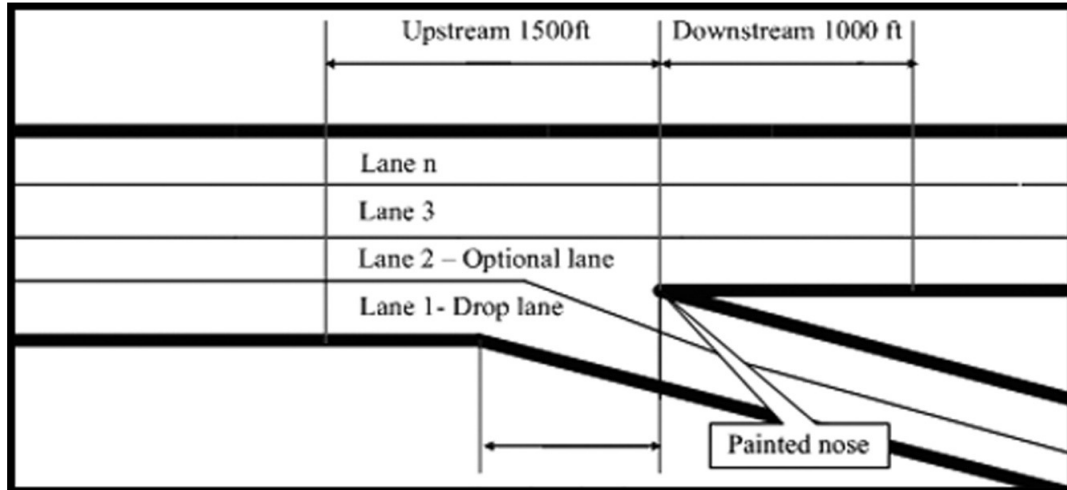
Figure 14 Segment Length for Type 3 at the Widely-Spaced Diverge Area
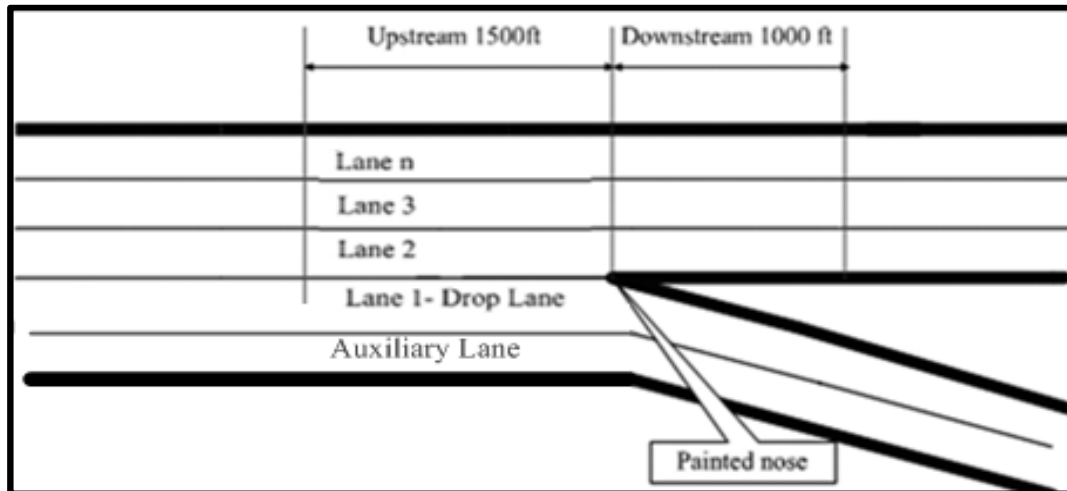
Figure 15 Segment Length for Type 4 at the Widely-Spaced Diverge Area

4.2.2 Closely-Spaced Freeway Segment

In order to understand how different design types on freeway closely-spaced freeway mainlines sections affect safety of freeways with closely spaced entrance and exit ramps, the study area was defined as follows. Three subsections were included for the closely-spaced freeway diverge sections. They are 1) a section starts from the merge point of an entrance ramp and ends at the painted nose of the downstream exit ramp, 2)

an influence area located within 1000 ft upstream of the merge point, and 3) an influence area located within 1000 ft downstream of the painted nose. The three sections were designated as section A, B and C, as shown in Figure 16.
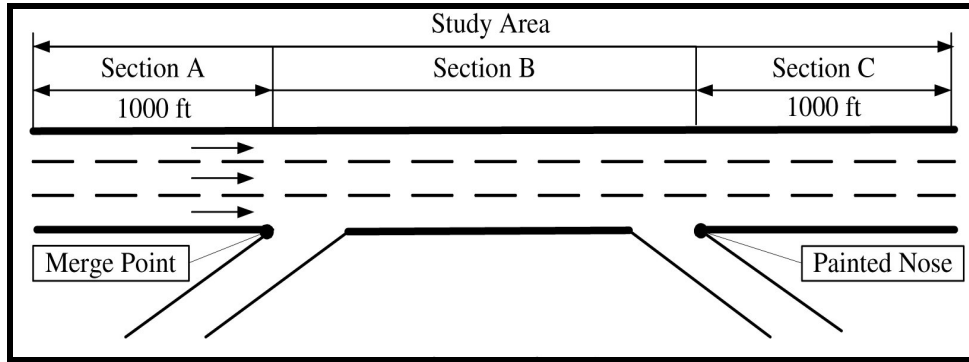
Figure 16 Study Segment at the Closely-Spaced Freeway Diverge Area

As mentioned before, three design types would be included in this study. Figure 17 illustrates the three design types, Type A, Type B, and Type C. For Type A, a one-lane entrance ramp is closely followed by one-lane exit and all exit ramps are taper-type. In this situation, both lane balance and the consistency of basic number of lanes are maintained for the arrangement. Type B is one-lane entrance with a two-lane exit. Type C is one-lane entrance with a one-lane exit. Both Type B and Type C are consistent in terms of the basic number of lanes.
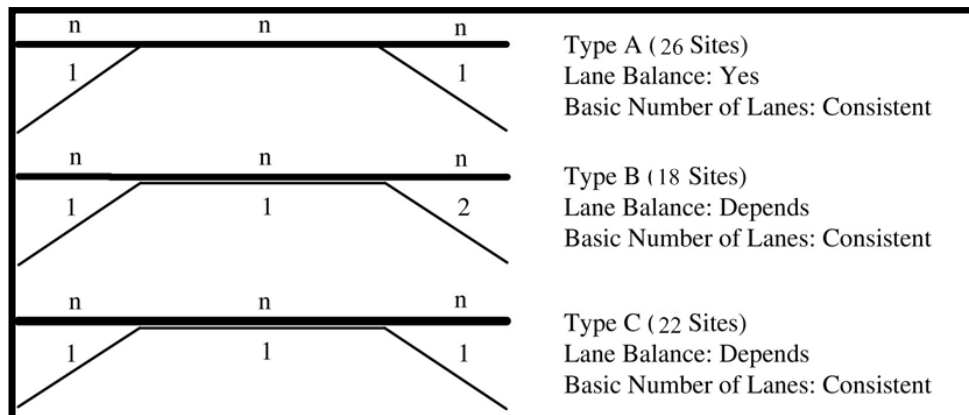
Figure 17 Three Design Types at the Closely-Spaced Diverge Area

4.2.3 Left-Side Off-Ramp

This study would examine the two most widely designs of left-side off-ramp in Florida, which is Type I and Type II. The segment length is identical to the comparable right-side off-ramps as Type 1 and Type 3 at widely-spaced freeway diverge areas. Two sections are included: 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 pained nose. Thus, the length of the diverge area equals 2500 ft for each site.

Type I has one exit lane where vehicles can make a left exit or continue on the freeway. It is comparable to Type 1 while it is a widely-spaced section at right-side off-ramp. Type II has two exit lanes. It is comparable to Type 3 design type while it is a widely-spaced section at right-side off-ramp. The two types are shown in Figure 18 and Figure 19 separately.
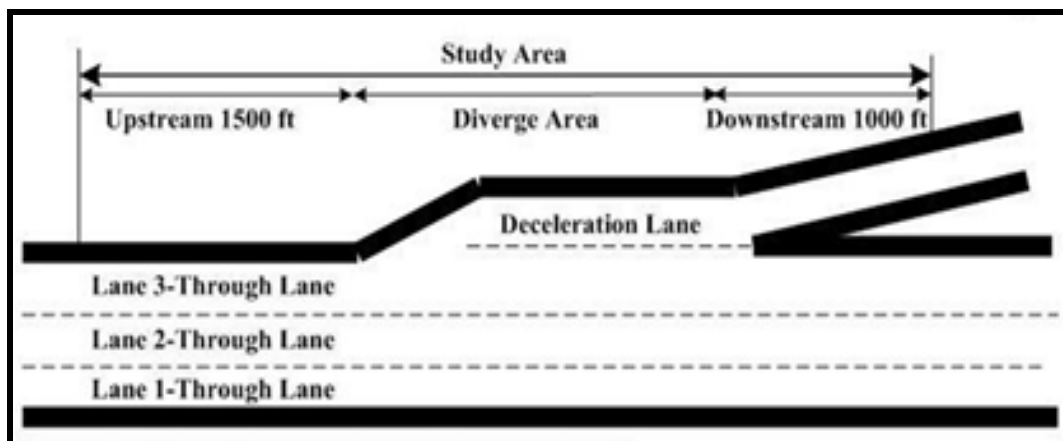
Figure 18 Segment Length of Type I on the Left-Side Off-Ramp
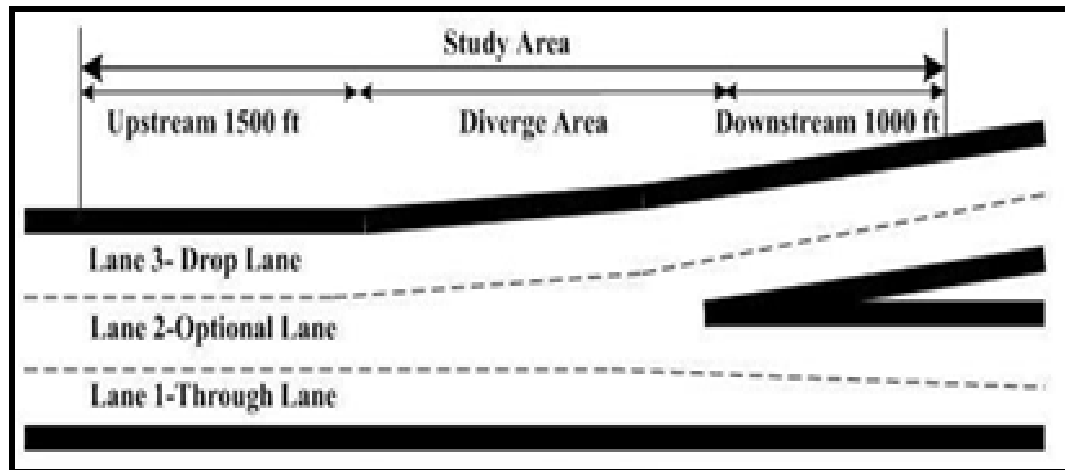
Figure 19 Segment Length of Type II on the Left-Side Off-Ramp

4.2.4 Exit Ramp Section

The crash frequency related to the segment length at selected sites. Usually, longer segment might have more potential crashes than shorter segments. Resende and Benekohal (40) did a comprehensive study on the segment lengths and the geometric variables relating to crash rates. The paper proved the essences of selecting the segment lengths.

The study area of the exit ramp section is from the beginning of the painted nose at freeway diverge area and to the end of ramp terminals. It varies slightly from past studies conducted by Bauer and Harwood (3), Janson et al. (21), Lord and Bonneson (26), Khorashadi (27) and McCart et al. (30). Part of their studies excluded the terminal sections from the entire exit ramps. However, different termination designs might influence the sections beyond.

Some studies defined study area as the entire ramp 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

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combination of these two sections might result in incorrect conclusions. Bauer and Harwood (3) only considered the entire ramp sections, they ruled out the all the rear-end crashes on the ramps. This might misrepresented the crash distribution and led to misunderstand of the contributing factors to the rear-end crashes. So this research defined the entire exit ramp as the study area. The following Figure 20 presents the study area by four ramp configurations.

Diamond Exit Ramp Segment Length

Out Connection Exit Ramp Segment Length
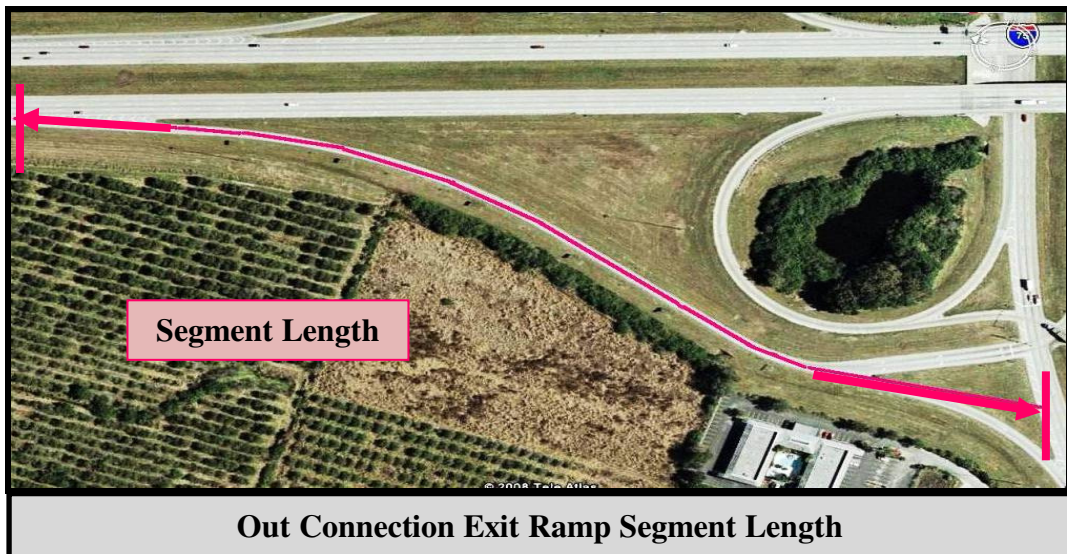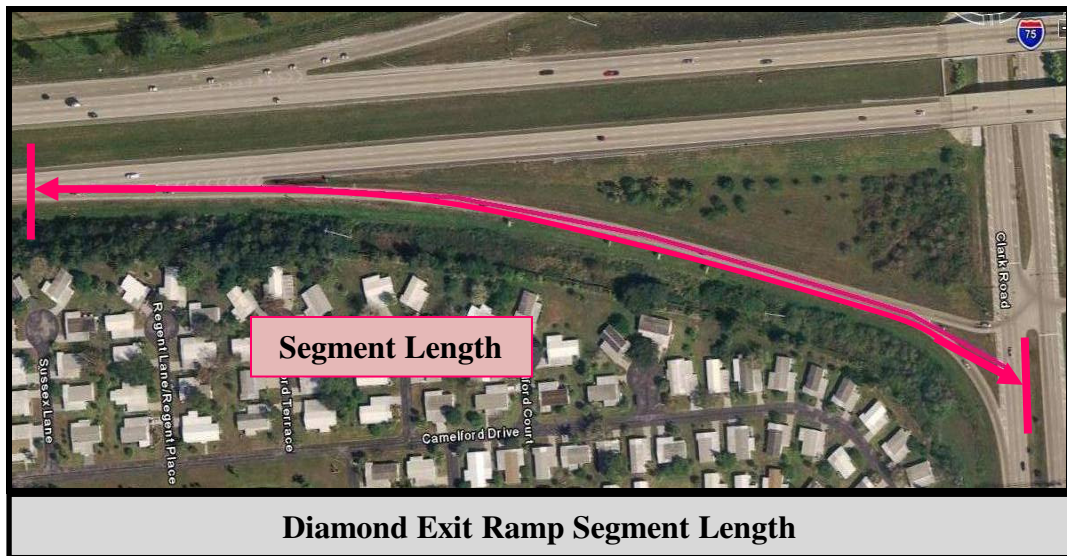
Figure 20 Study Areas for Four Ramp Configurations

Free-flow Loop Exit Ramp Segment Length
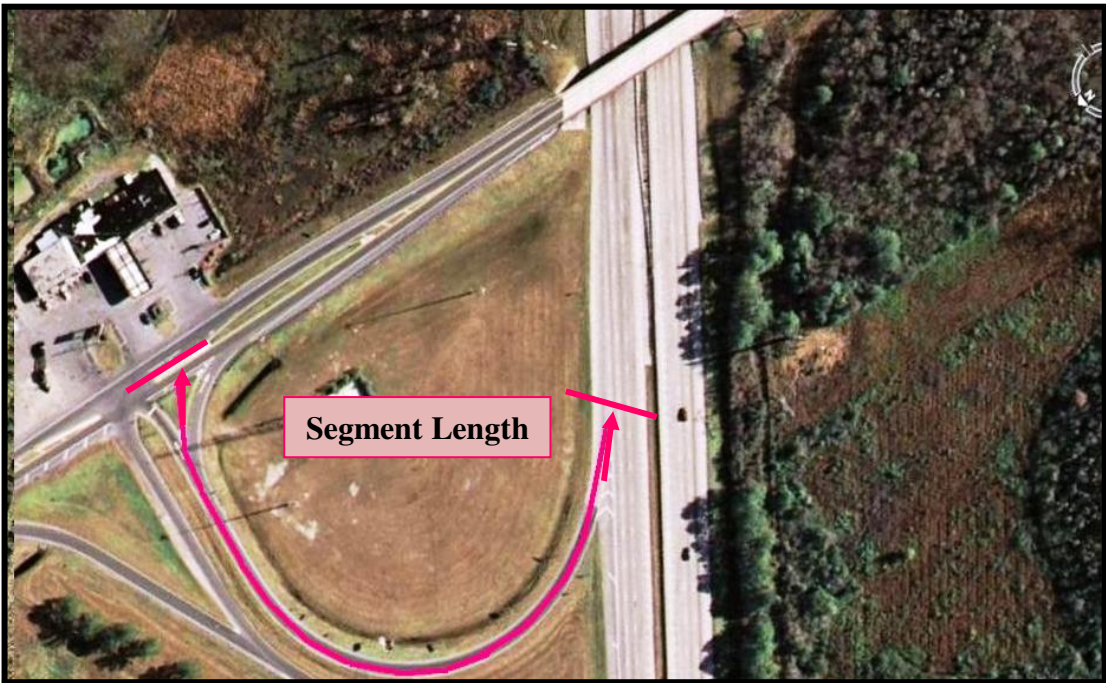
Parclo Loop Exit Ramp Segment Length

Figure 20 (Continued)

As shown in the figure above, four bold lines with two red arrows indicate the whole study area. Even they have special design patterns as they appear, the principles are unique. This is intended to raise the accuracy of the analysis and to obtain useful results.

4.3 Site Selection Procedure

The site selection procedures can be explained into three steps, field study, site collection, and site review. Field study is the first step to collect raw data such as the site type, site locations, and related geometric features. Based on the raw data, the site IDs could be obtained from Florida road identification systems: Straight-Line Diagram (SLD) and Florida Traffic Information CDs. Finally, all the selected sites are reviewed again to ensure the availability and accuracy of the site data.

4.3.1 Field Study

The field study collects the site location and geometric conditions, which should meet the requirements and criteria mentioned above. The photo maps were obtained from district traffic information CDs. For each site, several simple sketches with geometric information were checked to find the following data:

1) Freeway names;

2) Freeway travelling directions;

3) Exit Ramp locations (right/ left);

4) Basic number of lanes on freeway mainlines;

5) Maximal and Minimal speed limits on freeways;

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6) Deceleration lane lengths;

7) Upstream 1500 ft distances measurements from the painted nose and downstream 1000 ft distances measurements from the painted nose if it is a widely-spaced diverge area;

8) Upstream and downstream 1000 ft distance measurements from the merge point and diverge point if it is a closely-spaced diverge area;

9) Number of auxiliary lane if the site is a closely-spaced diverge area;

10) Upstream 1500 ft distances measurements from the painted nose and downstream 1000 ft distances measurements from the painted nose if it is a left-side off-ramp;

11) Whether large horizontal or curvature changes exists;

12) Ramp types (on/off);

13) Exit ramp configurations;

14) Ramp lengths;

15) Number of lanes on the ramp;

16) Ramp suggested/design speed limits;

17) Number of lanes changing on the ramp sections;

18) Ramp terminal control types;

19) Secondary roadway names;

20) Distances from the first upstream intersection on the secondary road;

21) Distances from the first downstream intersection on the secondary road;

4.3.2 Site Collection

After completing the first step, corresponding road IDs and mileposts were subtracted from SLD. The identification numbers and traffic volume for each segment were gathered from Florida Traffic Information (FTI) CDs. The detailed data are listed below:

1) Section and subsection number of the freeways;

2) Section and subsection number of exit ramp sections;

3) Milepost on the beginning and end of the segment length for diverge areas;

4) Milepost on the beginning and end of the segment length for exit ramps;

5) Site number for freeways segment;

6) Site number for exit ramp segment.

The purpose of using the section numbers and the mileposts is to consist with FDOT's crash database. Each section number contains eight digital codes to identify the particular 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 is the additional information to recognize the position on the roadway segment. Mileposts are calculated 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 an important index to obtain the traffic volume for each selected sites. Site IDs contain six digital numbers. The first two are the county number and the rest four digits are the sites recognized ID. For example, the site ID of I-75 at the Bruce B. Down's exit is '10' and '0153'. The AADT for this section could be obtained from AADT annual report by using the site ID.

4.3.3 Site Review

Each site and the related information would be 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.

4.4 Site Selection

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. For this reason, all the freeways are examined in order to get the reasonable sample size. Following the site selection criteria described before, a total of twelve Interstate Highways, ten expressways, one turnpike toll road and one parkway are reviewed and all the sites are collected from these freeways. These freeways provide high service level with high design standards. Figure 21 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.

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Eight districts are divided for the whole state, named as District One to District Eight. District One through District Seven have their local offices to manage each district. District eight is the toll road that are built, managed and maintained by all Florida offices. The district map in Figure 21, 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 all dispense in eight districts.

| Florida Interstate Highway | Florida District Map |
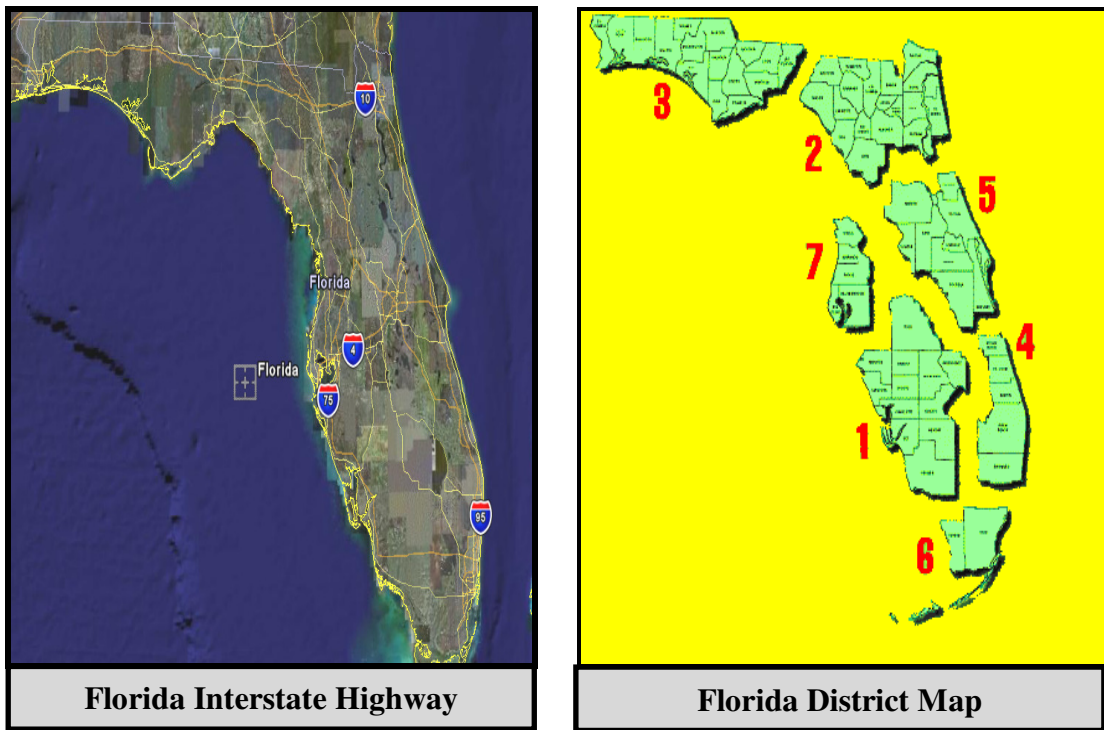
Figure 21 Florida Interstate Highway System and District Map

The sites were selected from the highway systems through eight districts. As a result, each site has the exit number containing the highway system and the district number. Table 1 lists the total highway systems in each district.

The task of site collection was one of the most time-consuming and tedious work in this study. Hundreds of sites are available and each site needed review carefully to make sure that all the collected data are correct. Area photos for each site were pulled

together. However, some sites were under reconstructions or closed for some time during the study period. Some sites did not have detailed site data such as AADT, especially at some expressways. If the sites did not have full information or they did not meet the sites requirements as mentioned before, they were excluded from the selected sites.

Table 1 Florida Freeway Distributions in Each District

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, South Crosstown Expressway, North Memorial Expressway;
Eight (Turnpike)	Florida Turnpike, Polk Parkway;

After reviewing all the area photos for the freeway diverge areas in the State of Florida, a total of over 600 sites were initially selected. Crash data for selected sites were obtained from the crash database maintained by FDOT. Also, other relevant data were collected such as freeway AADT and ramp AADT. Geometric data were obtained through reviewing area photos for each site.

To eliminate the impacts of other external factors, the selected sites were not located on large horizontal curves or vertical grades. According to the AASHOTO Green Book, freeway interchanges should avoid relative sharp horizontal or vertical curves (1). Based on the criteria mentioned above, Table 2 lists the final site numbers for each research subject. For the widely-spaced diverge area, 326 sites were selected, including 180 Type 1 sites, 68 Type 2 sites, 60 Type 3 sites and 18 Type 4 sites. While under the closely-spaced situation, the final database includes 66 segments; however, as limited sites for left-side exit ramps, only 11 sites were identified until now. And for the exit ramp sections, a total of 389 sides were selected.

Table 2 Number of Selected Sample Sites for Each Study Subject

Subject	Size Number	Design Type			
Widely-Spaced Diverge Area	326	Type 1	Type 2	Type 3	Type 4
		180	68	60	18
Closely-Spaced Diverge Area	66	Type A	Type B		Type C
		26	18		22
Left-side Off-Ramp	11	Type I		Type II	
		7		4	
Exit Ramp Section	389	Type 1	Type 2	Type 3	Type 4
		247	93	26	23

4.5 Crash Database

Based on the milepost range, crash data reported for each selected site was obtained from the Florida crash database. A three-year time frame, from 2004 to 2006, was defined in this study. In 2003, the FDOT renamed all of the freeway exit ramps in the whole state. Accordingly, the crash database updated the exit ramp numbers so that the crash data for freeway exit ramps before 2004 had some missing information and, sometimes cannot be matched with the data after 2004. Due to this reason, crash data were only selected after 2004 for further analysis. Eighty-six variables were originally enclosed in the FDOT crash database. Thus, each selected site had a three-year crash records containing all the crashes and related information.

4.6 Combination of Crash Data with Site Information

The final database included all the site information. For each selected site, the final database contained the geometric data, traffic data and crash related data. Figure 22 shows the example of part database.

Numb	Exit name	Ramp type	Ramp Configurations	Mainlane	Dist	SECTION NUMBER	Secondary name	Direction	paint no
1	I-75 EXIT 158-1	1	Diamond	I-75	1	01-075-000	Trucks Grade	S---N	8.259
2	I-75 EXIT 158-2	1	Diamond	I-75	1	01-075-000	Trucks Grade	N---S	8.775
3	I-75 EXIT 161-1	1	Diamond	I-75	1	01-075-000	Jones Loop Rd	SE---NW	11.544
4	I-75 EXIT 161-2	1	Diamond	I-75	1	01-075-000	Jones Loop Rd	NW---SE	12.073
5	I-75 EXIT 164-1	1	Diamond	I-75	1	01-075-000	Federal 17	S---N	14.788
6	I-75 EXIT 167-2	1	Diamond	I-75	1	01-075-000	Harbor View Rd	NW---SE	18.168
7	I-75 EXIT 170-1	1	Diamond	I-75	1	01-075-000	Kings Hwy	S---N	20.797
8	I-75 EXIT 170-2	1	Diamond	I-75	1	01-075-000	Kings Hwy	N---S	21.342
9	I-75 EXIT 101-1	1	Diamond	I-75	1	03-175-000	Collier Blvd	E---W	50.107
10	I-75 EXIT 123-1	1	Diamond	I-75	1	12-075-000	Corkscrew Rd	S---N	8.095
11	I-75 EXIT 123-2	1	Diamond	I-75	1	12-075-000	Corkscrew Rd	N---S	8.681
12	I-75 EXIT 128-1	1	Outer Connection	I-75	1	12-075-000	Alico Rd	S---N	12.23
13	I-75 EXIT 138-1	1	Diamond	I-75	1	12-075-000	Dr Martin Luther King	S---N	22.352
14	I-75 EXIT 138-2	1	Diamond	I-75	1	12-075-000	Dr Martin Luther King	N---S	22.907

Figure 22 Example of Final Database

CHAPTER 5

DATA ANALYSIS

5.1 Outline of Data Analysis

Historical crash data were analyzed to evaluate the safety performances of the two research subjects, the freeway diverge area and the exit ramp section. Quantitative investigations were conducted to find out the crash characteristics and the contributing factors to different types under various design situations.

If the freeway diverge area is a widely-spaced segment, cross-sectional comparisons were conducted to compare the effects of four design types. Following results were obtained:

1) The average crash frequency and average crash rate of selected freeway segments among four types were compared and the best safety performance among the four types was identified by comparing each type at a specific level of confidence;

2) Proportionality tests were conducted to identify the differences in target crash types among four design types on selected freeway segments and significantly higher percentages of the specific crash type were obtained;

3) Proportionality tests were conducted to identify the differences in crash severity among four types on selected freeway segments;

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4) The crash predictive models were developed to determine the contributing factors and their effects on the crashes at the selected freeway areas;

If the freeway diverge area is a closely-spaced segment, cross-sectional comparisons were conducted to compare the effects of three defined design types as well. Following results were obtained:

1) The average crash frequency and average crash rate of selected freeway segments among three design types were compared and the best safety performance among the three types was recognized by comparing all the three types at a specific level of confidence;

2) Proportionality tests were conducted for testing differences in target crash types among three design types on the selected freeway segments and significantly higher percentages of the specific crash type was obtained among the three design types;

3) Proportionality tests were conducted for testing differences in crash severity among three design types on the selected freeway segments;

4) The crash predictive models were developed to determine the contributing factors and their effects on the crashes at the specific freeway areas;

For the left-side off-ramps at the freeway diverge area, cross-sectional comparisons were conducted to compare the effects of two different design types with the comparable right-side off-ramps. Average crash frequency and average crash rate between selected freeway segments at left-side areas and right-side areas with two design types were compared. The differences of safety impacts between the left-side off-ramps and right-side

off-ramps were identified as well. A crash predictive model was developed to identify the crash characteristics for the left-side off-ramp at the freeway diverge area.

On the freeway exit ramp section, cross-sectional comparisons were conducted to compare the effects of four configurations. Following results were obtained:

1) The average crash frequency and average crash rate of selected entire exit ramp segments were compared and the best safety performance among the four configurations was identified by comparing the four configurations at a specific level of confidence;

2) Proportionality tests were conducted to test the differences in target crash types among four configurations on the selected segments and significantly higher percentages of the specific crash type was recognized;

3) Proportionality tests were conducted to test the differences in crash severity among four configurations;

4) One crash predictive model was developed to determine the contributing factors and their effects on the crashes at selected exit ramp segments;

5.2 Widely-Spaced Freeway Diverge Area

5.2.1   Crash Frequency and Crash Rate

From 2004 to 2006, a total of 7872 crashes were reported at selected freeway segments. The site with the highest crash frequency is located on the Interstate Highway 95 (I-95) in Miami-Dade County of Florida. The site picture is shown in Figure 23. During the three-year time period, 179 crashes were reported at the site, including 99 injury

crashes and 2 fatal crashes. Field observation was conducted to identify the undesirable driving behaviors and design elements which contributed to the high crash frequency at the particular location. The freeway segment is located on a five-lane freeway with a posted speed limit of 55 mph. The design type is found to be a type 4 exit ramp which is a two-lane exit ramp with the outer lanes of the freeway dropped at the exit gore. The AADT on the freeway is 224,000 vehicles per day. The ramp AADT is found to be 24,250 vehicles per day.

Field observation found that the dropped lane sometimes could trap drivers at its termination point. Drivers who mistakenly enter the dropped lane need to merge back into through lanes to continue on the freeway, creating more weaving conflicts around the gore area. Since the freeway AADT is relatively high, the increased weaving conflicts could result in some safety concerns at freeway diverge areas. Another potential safety concern found at the site is related with the high ramp AADT. During peak period, traffic waiting on exit ramps could spill back onto the major freeway, which will result in increased potential for rear-end crashes.
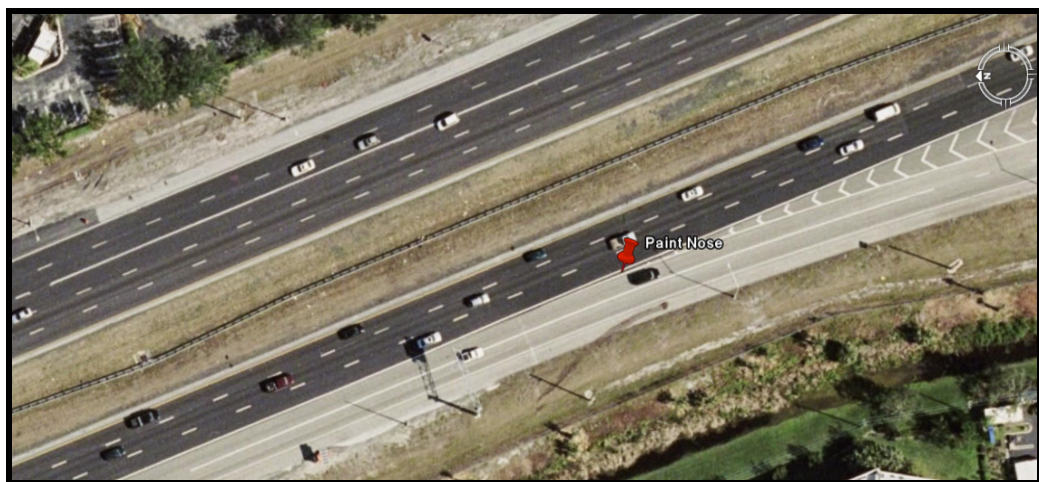
Figure 23 Site Picture of the Widely-spaced Freeway Diverge Area with the Highest Crash Frequency

Crash frequency at selected sites varies from 0 to 60 with a mean of 8.08 crashes per year. The collected crash data were divided into four different groups based on the design types mentioned before. Summary statistics of crash counts for four design types at widely-spaced diverge area are given in Table 3. On average, type 1, type 2, type 3 and type 4 design types reported 4.78, 12.82, 10.23, and 15.41 crashes per year at selected freeway segments, respectively.

Table 3 Descriptive Statistics of Crash Frequency by Four Design Types at Widely-Spaced Diverge Area

Type of Exit Ramp	N	Total	Mean	Std.	Max	Min
1	180	2583	4.78	3.69	18	0
2	68	2616	12.82	14.31	60	0.33
3	60	1841	10.23	7.65	29	1.33
4	18	832	15.41	11.64	42	0

The mean values of crash frequencies were compared in Figure 24 as well. The type 4 exit ramps have the highest average crash frequency (15.41 crashes per year per site), followed by the type 2 exit ramps (12.82 crashes per year per site). Type 1 exit ramps have the best safety performance in terms of the lowest average crash frequency reported at freeway diverge areas. In general, lane-balanced exit ramps were found to be safer as compared to those not lane-balanced. For one-lane exit ramps, lane-balanced exit ramps (type 1) reported 62.7% less crashes as compared to those not lane-balanced (type 2). For two-lane exit ramps, lane-balanced exit ramps (type 3) reported 33.6% less crashes as compared to those not lane-balanced (type 4).

The crash rates were also compared for four design types. For the widely-spaced diverge area, two different types of crash rates were used. One is defined based on the

freeway AADT. It is denoted as Crash Rate A (crashes per million vehicles per mile). The crash rate for a particular freeway segment can be calculated as follows:

$$R = \frac{1,000,000 \times A}{365 \times T \times V \times L}$$

(27)

where R is the crash rate at a freeway segment (crashes per million vehicles per mile); A is the number of crashes reported at the freeway segment (crashes per year); T is the number of years of study period (T=3); V is the AADT on freeway and/or exit ramp (veh/day); and L denotes the length of the freeway segment (2500 ft for all selected segments).
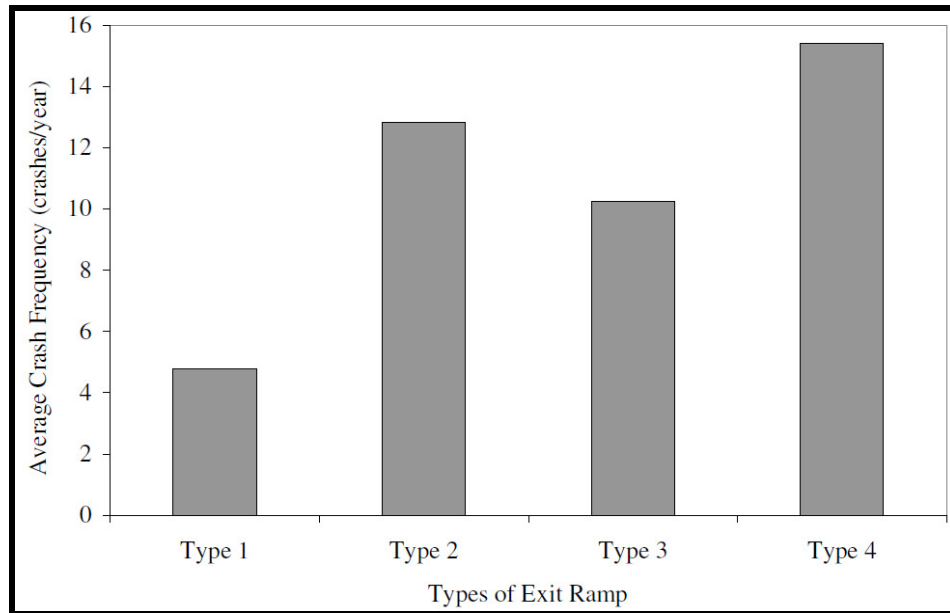
Figure 24 Comparison of Average Crash Frequency by Four Design Types at Widely-Spaced Diverge Areas

Another one is defined by joint consideration of both freeway AADT and ramp AADT. The combined AADT equals the square root of the multiplication of freeway AADT and ramp AADT ($V = \sqrt{AADT_{freeway} \times AADT_{ramp}}$). It is denoted as Crash Rate B compared to Crash Rate A.

Descriptive statistics for two types of crash rates were given in Table 4. For the first type of crash rate, it was reported 0.34, 0.57, 0.46 and 0.86 crashes per million vehicles per mile for Type 1, Type 2, Type 3 and Type 4 exit ramps respectively. For the second type of crash rate, 1.25, 2.22, 1.47 and 2.27 crashes per million vehicles per mile were calculated for the four design types accordingly.

Table 4 Descriptive Statistics of Crash Rates by Four Design Types at Widely-Spaced Diverge Areas

Type of Exit Ramp	N	Crash Rate A[a]				Crash Rate B[b]			
		Mean	Std.	Max	Min	Mean	Std.	Max	Min
1	180	0.34	0.22	1.25	0.00	1.25	0.90	5.04	0.00
2	68	0.57	0.47	1.97	0.05	2.22	1.86	7.53	0.12
3	60	0.46	0.41	1.18	0.06	1.47	0.96	3.71	0.29
4	18	0.86	0.66	4.68	0.00	2.27	0.37	4.77	0.00

a Crash rate defined by freeway AADT
b Crash rate defined by both freeway AADT and exit ramp AADT

Figure 25 compares the two types of crash rates by four design types. The comparison yields similar results. Again, type 1 exit ramps have the best safety performance in terms of the lowest crash rates at freeway diverge areas. Type 4 exit ramps have the highest average crash rates followed by the type 2 exit ramps. Depends on the definition of crash rate, for one-lane exit ramp, the lane-balanced exit ramps (type 1) have 40.4% to 43.7% lower crash rates as compared to those not lane-balanced (type 2). For two lane exit ramps, the lane-balanced exit ramps (type 3) have 35.2% to 46.5% lower crash rates as compared to those not lane-balanced (type 4).

t-tests were conducted to test if the differences in crash frequency and crash rates between different types of exit ramps are statistically significant. The calculated t values are summarized in Table 5. Most of the tests were found to be statistically significant with a 90% confidence level ($t_{0.05}=1.645$), which are highlighted in the table. More particularly,

type 2 exit ramps (not lane-balanced) have significantly higher crash frequency and crash rates as compared to type 1 exit ramps (lane-balanced). Type 4 exit ramps (not lane-balanced) have significantly higher crash frequency and crash rates as compared to type 3 exit ramps (lane-balanced).
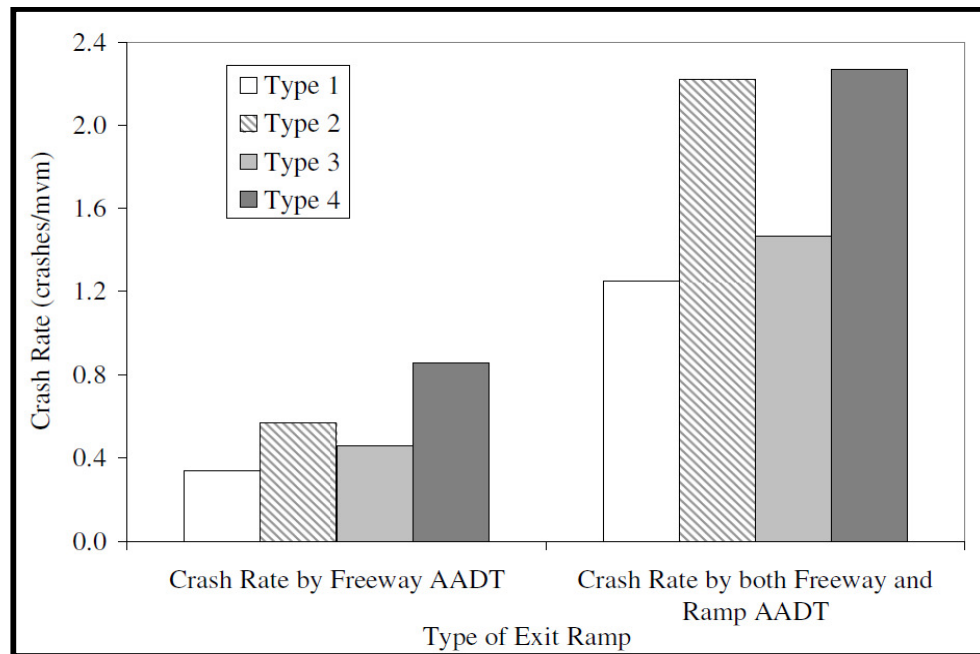
Figure 25 Comparison of Average Crash Rate by Four Design Types at Widely-Spaced Diverge Areas

Table 5 Statistical Tests for Crash Frequency and Crash Rate at Widely-Spaced Diverge Areas

Frequency/Rate	Comparison between Different Types of Exit Ramps					
	1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
Crash Frequency	**4.58**	**5.31**	**8.74**	-1.30	0.71	**2.21**
Crash Rate A[a]	**3.87**	**2.94**	**5.70**	-1.61	**1.75**	**2.71**
Crash Rate B[b]	**4.12**	1.56	**4.76**	**-2.91**	0.11	**3.45**

a Crash rate defined by freeway AADT
b Crash rate defined by both freeway AADT and exit ramp AADT

5.2.2 Crash Severity

The crashes reported at selected sites include 4108 PDO crashes, 3695 injury crashes and 69 fatal crashes. In this study, crash severity was compared for four design types by comparing the percentages of PDO crashes and injury plus fatal crashes. The exit ramps with lower percentages of injury plus fatal crashes were considered to be safer.

On average, the percentage of fatal plus injury crashes was found to be 48.47%, 48.39%, 47.58%, and 44.47% for type 1, type 2, type 3, and type 4 exit ramps respectively. Type 2 and type 4 exit ramps have slightly lower percentages of fatal plus injury crashes as compared to type 1 and type 3 exit ramps.

Proportionality tests were conducted to test if the difference in crash severity between different types of exit ramps was statistically significantly. The null hypothesis of the proportionality test is that the percentages of fatal plus injury crashes for two different types of exit ramps are equal. The test results are given in Table 6. With a 90% level of confidence ($Z_{0.05}$=1.645), none of the tests was found to be statistically significantly. The results suggest that the number and arrangement of lanes at widely-spaced freeway diverge area do not affect crash severity in a significant way.

Table 6 Proportionality Tests Results for Crash Severity at Widely-Spaced Diverge Areas

Crash Severity	Comparison between Different Types of Exit Ramps					
	1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
PDO	0.01	0.12	0.32	0.09	0.30	0.24
Injury/Fatal	-0.01	-0.13	-0.57	-0.12	-0.56	-0.45

5.2.3 Crash Type

Crash type is defined by the first harmful event in Florida crash database. The most frequent crashes at selected freeway segments were found to be rear-end crashes, followed by sideswipe crashes and angle crashes. Crash types for different types of exit ramps are given in Figure 26. As shown in Figure 26, type 2 and type 4 exit ramps reported slightly higher percentages of sideswipe and angle crashes as compared to type 1 and type 3 exit ramps. As mentioned before, both of these exit ramps have an outer lane of the freeway dropped at the exit gore. The dropped lane could trap drivers at its termination point and may create more weaving related crashes at freeway diverge areas.
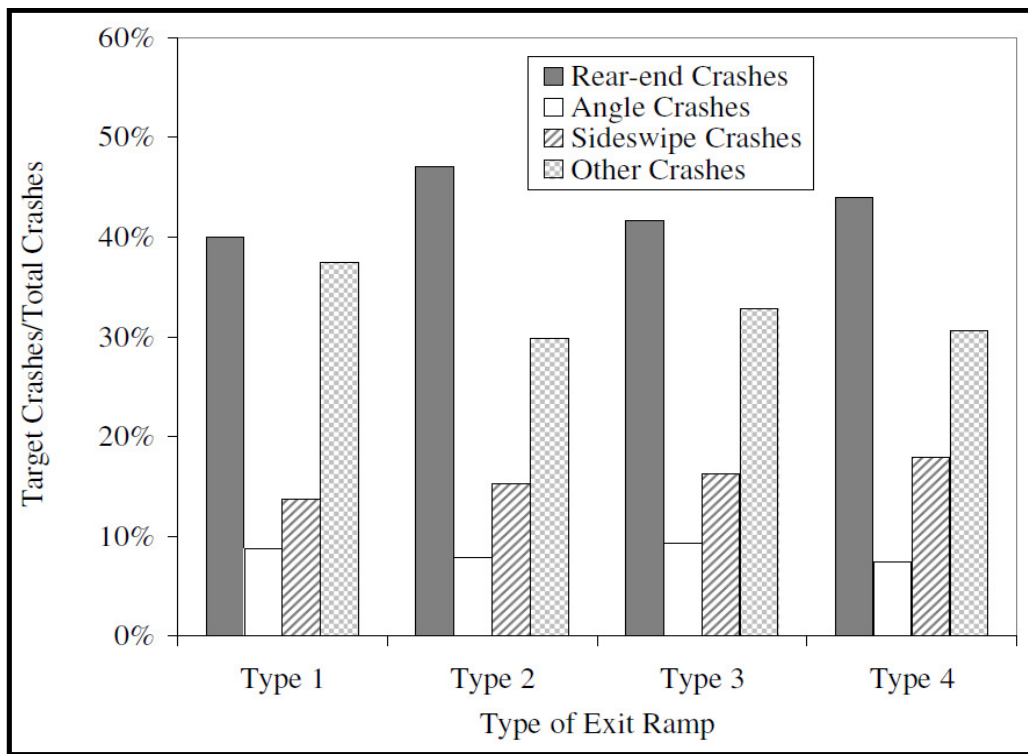
Figure 26 Comparison of Crash Types by Four Design Types at Widely-Spaced Diverge Areas

Proportionality tests were conducted for testing the differences in crash types between different types of exit ramps. The null hypothesis is that the percentages of a

particular type of crashes for two different types of exit ramps are equal. With a 90% level of confidence ($Z_{0.05}=1.645$), none of the tests were found to be statistically significant. The calculated Z statistic varies from -0.25 to 1.01. The results suggest that even though type 2 and type 4 exit ramps did report slightly higher percentages of sideswipe and angle crashes as compared to type 1 and type 3 exit ramps, the difference for the crash type is generally not statistically significant among four design types at the widely-spaced diverge area.

5.2.4 Crash Predictive Model

In this study, crash prediction models were developed to identify factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of the number and arrangement of lanes on freeway exit ramps. The dependent variable of the model is the average number of crashes per year reported at selected freeway segments. Twelve independent variables were initially considered. The definition of these independent variables is given in Table 7.

In the first stage, a combined model was developed in which four different types of exit ramps were defined by three indicator variables. However, variable interaction tests showed that the interactions between continuous variables and some indicator variables were statistically significant. To minimize the impacts of variable interactions, the combined model was separated into two different models, including a one-lane exit ramp model and a two-lane exit ramp model. The model for one-lane exit ramps used crash data reported at type 1 and type 2 sites, while the model for two-lane exit ramps used crash data obtained from type 3 and type 4 sites.

Table 7 Descriptive Statistics of Variables at Widely-Spaced Diverge Areas

Variables	Mean	Max.	Min.	Frequency
Total crash counts per year for one-lane exit ramp	7.00	55	0	248(76.07%)
Total crash counts per year for two-lane exit ramp	11.4	60	0	78(23.93%)
Basic number of lanes on freeways	3.12	5	1	326
Deceleration Lane Length (ft)	275.5	904	26	326
ADT in thousands on freeway sections	9.80	26	1	326
ADT in thousands on exit ramp sections	1.1	7.8	0.2	326
Posted speed Limit(mph)	67.89	75	55	326
Speed difference (mph)	49.4	59	33	326
Right shoulder width (ft)	10.2	13	8	326
Unbalanced exit ramp with one-lane exit				248
0 (Type 1)				180(72.58%)
1 (Type 2)				68(27.42%)
Unbalanced exit ramp with two-lane exit				78
0 (Type 3)				60(76.92%)
1 (Type 4)				18(23.08%)
Road Surface condition				326
0 (Dry)				295(90.49%)
1 (Wet)				31(9.51%)
Land type				326
0 (Primarily Business)				102(31.29%)
1 (Primarily Residential)				224(68.71%)
Road surface type				326
0 (Blacktop)				303(92.94%)
1 (Concrete)				23(7.06%)
Right shoulder type				326
0 (Paved)				160(49.08%)
1 (Unpaved)				166(51.92%)

The crash modeling started from Poisson models. For an adequate model, the scaled deviance and Pearson's χ^2 divided by the degrees of freedom shall be close to one. These statistics 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 χ^2 divided by the degrees of freedom were found to be 8.74 and 5.55 for one-lane and two-lane model respectively,

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.

Two negative binomial models were built relevant to the number of exit lanes. Six variables were not found to be statistically significant in both models. As a result, these variables were not included into the final model. The best models include six independent variables. The regression results of the best models are given in Table 8 and Table 9 for one-lane exit and two-lane exit respectively.

Table 8 Negative Binomial Model for One-Lane Exit Ramps at Widely-Spaced Diverge Areas

Variables	Coefficient	Std. Error	χ^2	$Pr > \chi^2$
Constant	3.9106	0.8362	21.87	<0.0001
Lane balance	0.5216	0.1118	21.77	<0.0001
Logarithm of deceleration lane length	0.2340	0.0704	11.05	0.0009
Logarithm of AADT in thousands on freeways	0.7055	0.1055	44.70	<0.0001
Logarithm of AADT in thousands on ramps	0.1523	0.0607	6.29	0.0121
Posted speed limit on freeway	-0.0375	0.0089	17.61	<0.0001
Right shoulder width	-0.1340	0.0541	6.13	0.0133
Log Likelihood	12925.50			
SD	265.70			
Pearson-χ^2	235.11			
SD/DF	1.10			
Pearson-χ^2/DF	0.98			
Dispersion Parameter	0.3594			

Table 9 Negative Binomial Model for Two-Lane Exit Ramps at Widely-Spaced Diverge Areas

Variables	Coefficient	Std. Error	χ^2	$Pr > \chi^2$
Constant	3.3263	1.1862	61.82	<0.0001
Lane balance	0.2714	0.2329	2.16	0.0972
Logarithm of deceleration lane length	0.2974	0.1197	2.05	0.0891
Logarithm of AADT in thousands on freeways	0.2978	0.0930	4.53	0.0333
Logarithm of AADT in thousands on ramps	0.4340	0.0835	27.00	<0.0001
Posted speed limit on freeway	-0.0158	0.0090	3.08	0.0790
Right shoulder width	-0.5300	0.0528	100.69	<0.0001
Log Likelihood	6749.73			
SD	83.64			
Pearson-χ^2	76.93			
SD/DF	1.18			
Pearson-χ^2/DF	1.08			
Dispersion Parameter	0.1319			

The scaled deviance divided by the degrees of freedom for both models are found to be 1.10 and 1.18 respectively. The Pearson's χ^2 divided by the degrees of freedom are 0.98 and 1.08. The statistics are reasonably close to one, indicating the fact that both models are adequately fitted. The final equations of the crash models are given as follows:

$$Y_{W1} = (X_1)^{0.2340}(X_2)^{0.7055}(X_3)^{0.1523}\exp(3.9106+0.5216X_4 -0.0375X_5 -0.1340X_6) \quad (28)$$

$$Y_{W2} = (X_1)^{0.2974}(X_2)^{0.2978}(X_3)^{0.4340}\exp(3.3260+0.2714X_4 -0.0158X_5 -0.5300X_6) \quad (29)$$

Where,

Y_{W1} = expected average crash frequency in a widely-spaced freeway segment with

one-lane exit ramp (crashes/year);

Y_{W2} = expected average crash frequency in a widely-spaced freeway segment with

two-lane exit ramp (crashes/year);

X_1 = length of the deceleration lane (ft);

X_2 = mainline freeway AADT for the direction of travel in which the ramp is

located (vehicles in thousands per day);

X_3 = ramp AADT (vehicles in thousands per day);

X_4 = 1 if the exit ramp is not lane balanced, 0 otherwise;

X_5 = posted speed limit on freeway (mph);

X_6 = right shoulder width (ft);

For both models, all selected independent variables are statistically significant with a 90% confidence level. The coefficients for both freeway AADT and ramp AADT are positive, indicating the fact that the number of crashes increase with the increase of freeway and ramp AADT.

The positive signs for the length of deceleration lane in both models indicate that crash counts increase with the increase of the deceleration lane length. This conclusion is not consistent with the results of Bared et al.'s study in which it was found that increasing deceleration lane length will reduce crash frequency. In fact, the results of past studies regarding the safety impacts of the deceleration lane length are not quite consistent. For example, a more recent study found that using long deceleration lane creates more weaving maneuvers at freeway diverge areas. In addition, a long deceleration lane will

encourage drivers accelerate the speeds before they exit the main roads. Thus, it has the potential to increase crash risks at freeway diverge areas.

The coefficients for posted speed limit in both models are negative, implying the fact that crash counts decrease with the increase of the posted speed limit of the freeway. This result is relatively counter intuitive. A possible explanation is that posted speed limit may be correlated with other variables which were not included into our models. For example, it is very possible that a freeway with higher posted speed limit is also designed according to higher standards. Thus, higher posted speed may be correlated wider lane width, better lighting conditions, better signing or pavement marking; and these missing factors could be correlated with low crash frequency at freeway diverge areas.

The coefficients for the indicator variables for lane balance are positive for both models, indicating the fact that lane-balanced exit ramps have lower crash frequency as compared to those not lane balanced. This conclusion is consistent with the results of our cross-sectional comparisons.

The coefficients of the model can be used to quantify the safety benefits of using lane-balanced exit ramps. Based on the models, replacing a type 1 exit ramp (lane balanced) with a type 2 exit ramp (not lane-balanced) will increase crash counts at freeway diverge areas by exp (0.5216-0)-1=68.47%. Replacing a type 3 ramp (lane balanced) with a type 4 ramp (not lane-balanced) will increase crash counts at freeway diverge areas by exp (0.2714-0)-1=31.18%.

5.3 Closely-Spaced Freeway Diverge Area

5.3.1   Overall Crash Frequency

From 2004 to 2006, a total of 6249 crashes were reported at selected freeway segments. Crash frequency at selected locations varies from 0 to 166 with a mean of 31.6 crashes per year. The collected crash data were divided into three different groups based on the arrangement of lanes on freeway mainlines and ramps. Summary statistics of crash frequency for different types of lane arrangements were given in Table 10. On average, type A, type B, and type C freeway segments reported 34.1, 38.0, and 23.2 crashes per year at selected locations, respectively. The type B freeway segments reported the highest average crash frequency (38.0 crashes per year per site), followed by type A freeway segments (34.1 crashes per year per site). The type C freeway segments have the best safety performance in terms of the lowest average crash frequency (23.2 crashes per year per site) at selected locations.

Table 10 Descriptive Statistics of Crash Frequency at Closely-Spaced Diverge Areas

Arrangement Type	Number of Sites	Mean	Std.	Maximum	Minimum
A	26	34.1	31.80	166	0
B	18	38.0	20.33	95	12.7
C	22	23.2	15.29	74	3.7

t-tests were conducted for comparing the crash frequency between selected freeway segments with different types of lane arrangements. With a 90% level of confidence ($t_{0.05}$=1.645), none of the tests was found to be statistically significant. In reality, a number of factors other than the types of lane arrangements may affect the safety performance of selected freeway segments. It is not appropriate to compare the safety of different types of arrangements without considering the impacts of these external factors.

Crash rate was also compared for freeway segments with different types of lane arrangements. The crash rate, crashes per million vehicles per mile for a particular freeway segment, can be calculated as follows:

$$R = \frac{1,000,000 \times A}{365 \times T \times V \times L}$$

(30)

where R is the crash rate at a freeway segment (crashes per million vehicles per mile); A is the number of crashes reported at the freeway segment (crashes per three years); T is the number of years of study period (T=3); V is the ADT on freeway mainline; and L denotes the length of the study area which equals the length of the section B plus 2000 ft.

Descriptive statistics for crash rates are given in Table 11. Again, the type C arrangement has the best safety performance in terms of the lowest crash rate at selected freeway segments. The type B arrangement has the highest average crash rate followed by the type A arrangement. t-Tests were conducted to test if the differences in crash rate between different types of freeway segments was statistically significant. In this time, all of the t-tests were found to be statistically significant with a 90% confidence level.

Table 11 Descriptive Statistics for Crash Rates at Closely-Spaced Diverge Areas

Arrangement Type	Number of Sites	Mean	Std.	Maximum	Minimum
A	26	0.72	0.52	2.00	0.00
B	18	1.28	1.07	3.93	0.27
C	22	0.37	0.20	1.03	0.07

The crashes reported at selected freeway segments include 3316 PDO crashes, 2799 injury crashes and 39 fatal crashes. In this study, crash severity was compared for different types of lane arrangements by comparing the percentages of PDO crashes and

injury plus fatal crashes. The lane arrangements with lower percentages of injury plus fatal crashes are considered to be safer.

On average, the percentage of fatal plus injury crashes was found to be 38.45%, 52.45%, and 40.90% for the type A, type B, and type C arrangement respectively. Crash severity for freeway segments with different types of lane arrangements is compared in Figure 27. As shown in Figure 27, the type A freeway segments reported the lowest percentage of injury plus fatal crashes while the type B freeway segments reported the highest. Proportionality tests were conducted to test if the difference in crash severity between different types of lane arrangements were statistically significantly. With a 90% level of confidence, all of the tests were found to be statistically significant.
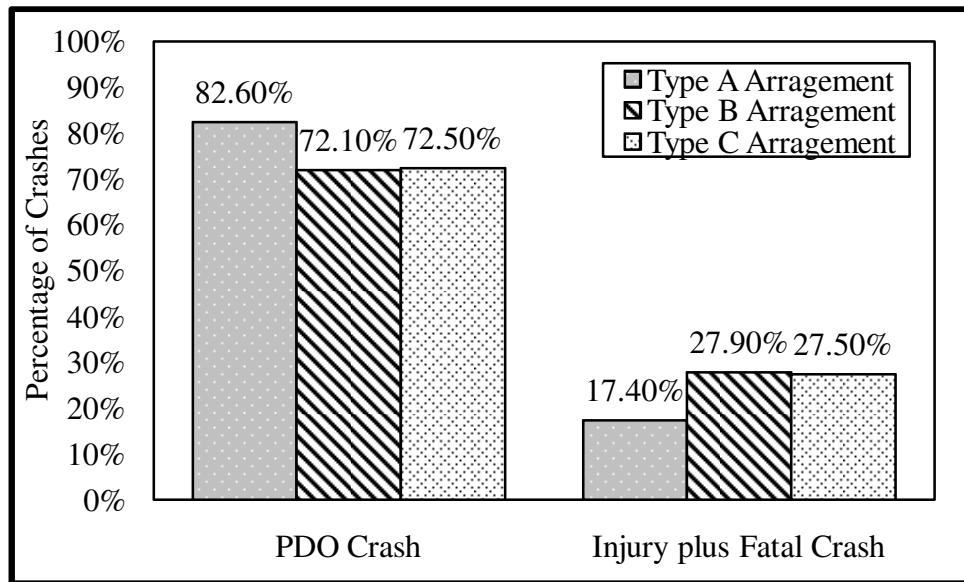
Figure 27 Comparison of Crash Severity for Three Arrangements at Closely-Spaced Diverge Areas

Crash type is defined by the first harmful event in the crash database maintained by the FDOT. The most frequent crashes at selected freeway segments were found to be rear-end crashes, followed by sideswipe crashes and angle crashes. Crash types for different

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types of freeway segments are compared in Figure 28. As shown in Figure 28, the type B and type C freeway segments reported relatively higher percentages of sideswipe and angle crashes as compared to the type A freeway segments. The type A freeway segments reported the highest percentage of rear-end crashes.
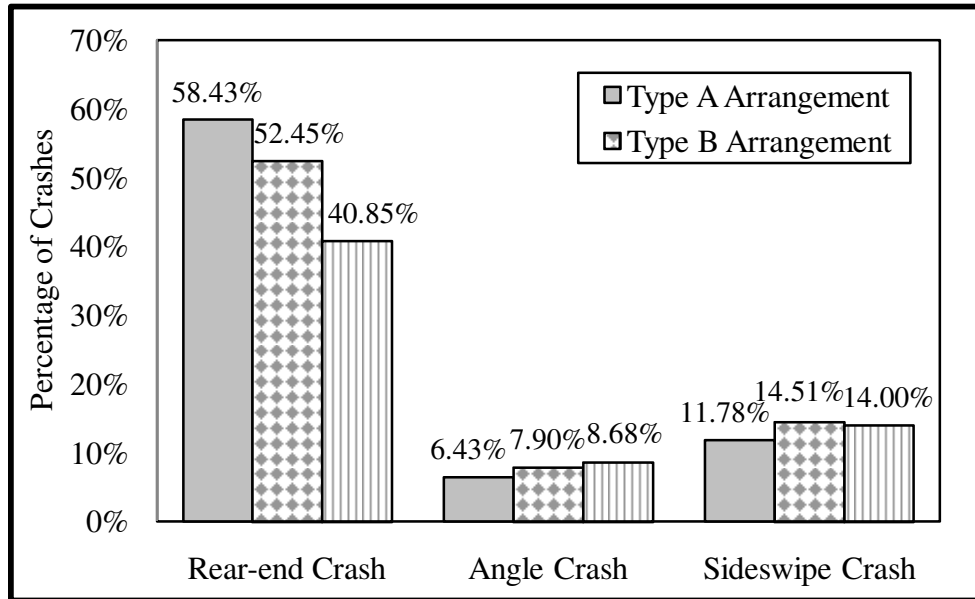
Figure 28 Comparison of Target Crash Type for Three Arrangements at Closely-Spaced Diverge Areas

Proportionality tests were conducted for testing the differences in crash types between different types of freeway segments. The null hypothesis is that the percentages of a particular type of crashes for two different types of freeway segments are equal. The results for proportionality tests are given in Table 12.

Table 12 Proportionality Tests Results of Target Crash Types at Closely-Spaced Diverge Area

Proportionality Tests	Rear-end Crashes	Sideswipe Crashes	Angle Crashes
Type A vs. Type B Arrangements	**4.07**	**-2.63**	**-1.95**
Type A vs. Type C Arrangements	**11.9**	**-2.15**	**-2.85**
Type B vs.Type C Arrangements	**7.25**	0.50	-0.90

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With a 90% level of confidence ($Z_{0.05}=1.645$), it was found that the type A freeway segments reported significantly higher percentages of rear-end crashes as compared to the type B and type C freeway segments. The type B and type C freeway segments reported significantly higher percentages of angle and sideswipe crashes as compared to the type A freeway segments.

The crash type analysis results explained the reason why the type A freeway segments reported lower percentages of injury plus fatal crashes than the type B and C freeway segments. As mentioned before, both type B and C freeway segments are designed with continuous auxiliary lanes between closely spaced entrance and exit ramps. Due to the presence of the continuous auxiliary lanes, weaving segments were formed between entrance and exit ramps for the type B and C freeway segments. Thus, type B and C freeway segments reported relatively higher percentages of weaving related crashes, such as sideswipe crashes and angle crashes than type A freeway segments; and these crashes are usually associated with more severe results as compared to rear-end collisions.

5.3.2 Crash Prediction Models

As mentioned before, a number of factors other than the types of lane arrangements may affect the safety performance of selected freeway segments. It is not appropriate to compare the safety of different types of lane arrangements without considering the impacts of these external factors. In this study, crash prediction models were developed to identify the factors that affect the safety performance of selected freeway segments. Two different types of crash prediction models were developed, including a total crash model and a severe crash model.

The dependent variable of the total crash model is the total number of crashes reported at each selected freeway segment per year. Since weaving is an important consideration for freeway segments with closely spaced entrances and exits, a weaving crash model was also fitted. The dependent variable of the weaving crash model is the frequency of side-swipe crashes reported at each selected freeway segment per year. Twelve independent variables were explored when developing the crash models. Descriptive statistics for these variables are given in Table 13.

Table 13 Descriptive Statistics for Initially Considered Independent Variables at Closely-Spaced Diverge Areas

Variables	Min.	Max	Mea	Frequency
Basic number of lanes on freeways	2	6	3.16	66
Distances between entrance and exit ramps (miles)	0.08	0.50	0.35	66
ADT in thousands on freeway mainlines	28.5	282	184	66
ADT in thousands on entrance ramps	3.20	18.0	9.37	66
ADT in thousands on exit ramps	2.50	25.8	8.92	66
Right shoulder width (ft)	6	12	10.0	66
Posted speed limit on freeway mainlines				66
1 (posted speed limit equals 55 mph)				17(25.76%)
0 (posted speed limit equals 70 mph)				49(74.24%)
Type A arrangement				66
1 (Type A)				26(39.40%)
0 (others)				40(60.60%)
Type B arrangement				66
1 (Type B)				18(27.27%)
0 (others)				48(72.73%)
Road Surface condition				66
0 (Dry)				55(83.33%)
1 (Wet)				11(16.67%)
Land type				66
0 (Primarily Business)				42(63.64%)
1 (Primarily Residential)				24 (36.36%)
Road surface type				66
0 (Blacktop)				36(54.55%)
1 (Concrete)				30(45.45%)
Right shoulder type				66
0 (Paved)				41(62.12%)
1 (Unpaved)				25(37.88%)

Stepwise regression method was used to determine the variables that should be included into the crash models. To be included into the model, the variable must be significant at a 90% level of confidence. In addition, the correction matrix was estimated to ensure that there was no multicollinearity problem between selected independent variables. The modeling procedure started from the Poisson regression model. For both total and weaving crash models, overdispersion was observed, which indicated the appropriateness of using the NB models.

Different functional forms were tested. The regression results are given in Table 14 and Table 15. The best total crash model has 6 independent variables plus an interaction term. The independent variables include the freeway mainline ADT, number of lanes on mainlines, the entrance ramp ADT, an indicator variable for the posted speed limit on freeway mainlines, and two indicator variables for the type of arrangements. The segment length, which equals the distance between entrance and exit ramps plus 2000 ft, was modeled as an offset. The final equation for the total crash model is given as follows:

$$Y_{CT} = L * ADT_E^{0.3815} \exp(-0.9298 + 0.397 Type_A + 0.757 Type_B + 0.009 ADT_M$$
$$+0.723 Lanes - 0.002 ADT_M L + 0.8520 Speed) \tag{31}$$

Where,

Y_{CT} = expected total crash frequency in a closely-spaced freeway segment

(crashes/year);

L= distance between on-ramp and following off-ramps plus 2000 ft (mi);

ADT_E = freeway entrance ADT in thousands;

$Type_A$ = indicator variable (= 1 for type A arrangement, 0 otherwise);

$Type_B$ = indicator variable (= 1 for type B arrangement, 0 otherwise);

ADT_M = freeway mainline ADT in thousands;

Lanes = basic number of lanes on freeways;

ADT_ML = mainline ADT * number of lanes (interaction term); and

Speed = indicator variable for posted speed limit on freeway mainlines (=1 if the

posted speed limit equals 55 mph, 0 if the posted speed limit equals 70

mph).

Table 14 Regression Results for the Total Crash Model at Closely-Spaced Diverge Areas

Variables	Coefficient	Std. Error	χ^2	$Pr > \chi^2$
Constant	-0.9298	1. 0521	0.78	0.3768
Type A arrangement	0.3791	0.2117	3.21	0.0733
Type B arrangement	0.7573	0.2259	11.24	0.0008
Number of lanes on freeway mainlines	0.7232	0.2581	7.85	0.0051
Mainline ADT in thousands	0.0092	0.0052	3.12	0.0773
Interaction term (mainline ADT*number of lanes)	-0.0019	0.0012	2.63	0.1051
Logarithm of entrance ramp ADT	0.3815	0.1382	7.26	0.0071
Posted speed limit on freeway mainlines (=1 if the posted speed limit is 55mph; =0 70 mph ;)	0.8520	0.0189	15.91	<0.0001
Log Likelihood	5520.98			
SD	72.69			
Pearson-χ^2	61.8			
SD/DF	1.25			
Pearson-χ^2/DF	1.06			
Dispersion Parameter	0. 2469			

Four independent variables were found to be statistically significant in the severe

crash model. They are: the number of lanes on freeway mainlines, the logarithm of

entrance ramp ADT, the posted speed limit on freeway mainlines, and one indicator

variables for the type B arrangements. The segment length, which equals the distance between entrance and exit ramps plus 2000 ft, was modeled as an offset. The final equation for the weaving crash model is given as follows:

$$Y_{CS} = L * ADT_E^{0.3867} \exp(-0.0401 + 0.7025 Type_B + 0.2588 Lanes + 0.5051 Speed) \quad (32)$$

Where,

Y_{CS} = expected severe crashes in a closely-spaced freeway segment (crashes/year);

L= distance between on-ramp and following off-ramps plus 2000 ft (mi);

ADT_E = entrance ramp ADT in thousands;

$Type_B$ = indicator variable (= 1 for type B arrangement, 0 otherwise);

Lanes = number of lanes on freeway mainlines; and

Speed = indicator variable for posted speed limit on freeway mainlines (=1 if the posted speed limit equals 55 mph, 0 if the posted speed limit equals 70 mph).

The coefficients for posted speed limit in both models are positive, implying the fact that crash counts decrease with the increase of the posted speed limit of the freeway. A possible explanation is that posted speed limit may be correlated with other variables which were not included into our models. For example, it is very possible that a freeway with higher posted speed limit is also designed according to higher standards. Thus, higher posted speed may be correlated with wider lane width, better lighting conditions, better signing or pavement marking; and these missing factors could result in the lower crash frequency reported at selected freeway segments.

With the crash prediction models, one can compare the safety performance of different types of lane arrangements by taking into account the impacts of various external factors. For example, based on the crash prediction models, if other factors remain constant, a type A arrangement will result in exp (0.3791)-1=46% more total crashes than does a Type C arrangement. Similarly, a type B arrangement will result in 113% more total crashes and 102% more severe crashes as compared to a type C arrangement. Again, the crash prediction models show that the type C arrangement has the lowest number of total crashes; the Type B arrangement has the highest number of total crashes and severe crashes.

Table 15 Regression Results for the Severe Crash Model at Closely-Spaced Diverge Areas

Variables	Coefficient	Std. Error	χ^2	Pr $>\chi^2$
Constant	-0.0401	0.4207	0.01	0.9240
Type B arrangement	0.7025	0.1473	22.76	<0.0001
Number of lanes on freeway mainlines	0.2588	0.0692	13.97	0.0005
Logarithm of entrance ramp ADT in thousands	0.3867	0.1293	8.95	0.0028
Posted speed limit on freeway mainlines (=1 if the posted speed limit is 55mph; =0 70 mph ;)	0.5051	0.196	6.64	0.0099
Log Likelihood	543.00			
SD	71.31			
Pearson-χ^2	68.27			
SD/DF	1.17			
Pearson-χ^2/DF	1.12			
Dispersion Parameter	0.1014			

5.4 Left-Side Off-Ramp

5.4.1 Crash Frequency and Crash Rate

Cross-sectional comparisons were conducted in the study to compare the average crash frequency and crash rate by the two defined types mentioned above with comparable two right-side off-ramps. It is noticed that the site number is limited for the left-side off-ramps. The selected comparable right-side off-ramps should have similar traffic and geometric features as the left-side off-ramps. The crash frequency at selected sites varies from 0 to 20 crashes per year for all the sites. The collected crash data were divided into four different groups based on the design types. Summary statistics of crash counts by each type were given in Table 16.

Table 16 Description of Crash Frequency and Crash Rate by Two Design Types on Left-Side Off-Ramps Comparable to Right-Side Off-Ramps

Average Crash Frequency (crashes per year)					
Design Type	N	Mean	Std.	Maximum	Minimum
I^*	53	5.14	3.18	14.67	1.67
I	7	8.29	7.52	19.67	1.33
II^*	10	5.93	5.76	16.67	0.00
II	4	6.00	4.55	12.67	2.67
Average Crash Rate (crash per million vehicle per mi)					
Design Type	N	Mean	Std.	Maximum	Minimum
I^*	53	0.30	0.13	0.66	0.08
I	7	0.38	0.22	0.75	0.14
II^*	10	0.32	0.16	0.94	0.00
II	4	0.35	0.10	0.43	0.19

On average, the type I^*, type I, type II^* and type II design types reported 5.14, 8.29, 5.93, 6.00 crashes per year at selected freeway segments, respectively. The type I ramp (left-side off-ramps with one–lane exit) has 60% more crashes than the type I^* (right-side off-ramp with one-lane exit). Also Type I (one-lane exit on the left-side off-ramp) has the

highest average crash frequency (8.29 crashes per year per site), followed by the Type II (two-lane exit on the left-side off-ramps).

Type I* exit ramps have the best safety performance in terms of the lowest average crash frequency reported at freeway diverge areas. In general, the right-side off–ramps were found to be safer as compared to those on the left-side off-ramps, especially for one-lane exit. For two-lane exit ramps, the average crash frequency on the left-side (Type II) is 1.2% more than Type II* (right-side off-ramps). Descriptive statistics for crash rates are given in Table 16 as well. The comparison of two different crash rates yields similar results. Again, type I* exit ramps have the best safety performance in terms of the lowest crash rates at freeway diverge areas. And type I ramp has the highest crash rates. The crash rates for type II* and type II ramps are similar.

t-tests were conducted to test if the differences in crash frequency and crash rate between different types of exit ramps are statistically significant. The test results indicate that the differences of crash frequency and crash rates between four ramps were found not to be statistically significant with a 90% confidence level ($t_{0.05}$=1.645). One possible reason might because of limited sample size for the left-side off-ramps compared with that of the right-side off-ramps. It is also possible that the main causation of overall crashes at the diverge areas is not the side of exit, but the exit itself.

The freeway diverge section and the vicinity area is always a critical section and the chance to involve in a crash is relatively not depending on the side of the exit ramps. For one-lane exit, drivers need take the similar maneuvers, as changing lanes and decreasing speeds to the exit lane. For two-lane exit with an optional lane, drivers have the flexibility to either continue or exit freeways without aggressive lane change maneuvers.

5.4.2   Crash Severity

In this study, crash severity was compared for different types of exit ramps by comparing the percentages of PDO crashes and injury plus fatal crashes. The exit ramps with lower percentages of injury plus fatal crashes were considered to be safer. Figure 29 compares the percentage of PDO and injury plus fatal crashes by each type. On average, the percentage of fatal plus injury crashes was found to be 36.18%, 67.62%, 37.98%, and 68.13% for type I*, type I, type II*, and type I exit ramps, respectively. It is obvious that both type I and type II exit ramps have relatively high percentage of severity crashes as compared to type I* and type II*.
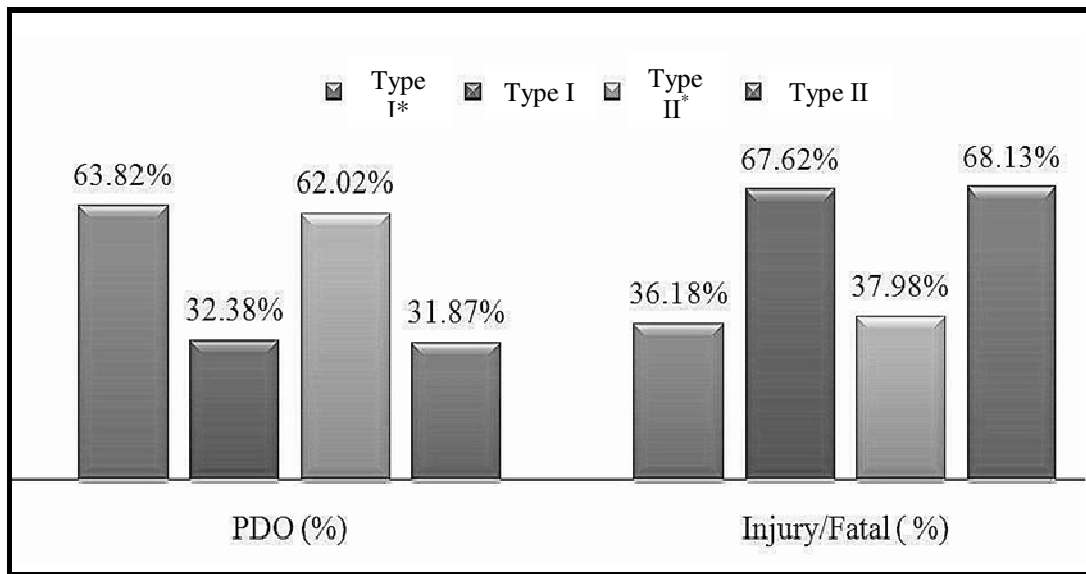
Figure 29 Comparison Severe Crashes for Left-Side Off-Ramps with Comparable Right-Side Off-Ramps

Proportionality tests were conducted to test if the difference in crash severity between different types of exit ramps was statistically significant. The null hypothesis of the proportionality test is that the percentages of fatal plus injury crashes for two different types of exit ramps are equal. The test results are given in Table 17. With a 90% level of

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confidence ($Z_{0.05}=1.645$), Type I was found to have statistically significantly higher percentage of severity crashes than Type I*. But for two-lane exit, the difference is not significant. This might be because of the limited number of available sites for the study. Also it is noticed that two-lane exits have higher percentage of injury plus fatal crashes comparing to one-lane exit, it could be one of the reason that increasing the number of exit lanes would cause an increasing in severe crashes for both right-side and left-side exits.

Table 17 Proportionality Test Results of Crash Severity for Left-Side Off-Ramps with Right-Side Off-Ramps

Crash Severity	Type I* vs. Type I	Type II* vs. Type II
PDO	**-1.70**	-1.10
Injury/Fatal	**1.70**	1.10

The results suggest that even though the average crash frequency and crash rate did not appear significantly different for left-side and right-side off-ramps, the one-lane left-side off-ramps did affect crash severity in a significant way than one-lane right-side off-ramps at freeway diverging areas. This could be explained by the higher approaching speed which usually causes severe crashes. When vehicle approach the diverge area, drivers used to maintain a high speed on the left lane compared to those vehicles travelling on the right-side exit lanes. The probability of fatal injury crashes increases rapidly by the increment of the travelling speeds (44).

The author also noticed that the speed differentials between exiting vehicles and through movement vehicles are obviously different for left-side off-ramps with right-side off-ramps. From field observation, exiting vehicle decrease speeds gradually if the exit ramp is on the right-side. However, when traffic approaches left-side off-ramp, the exiting vehicles are travelling at a lower speed compared to those on the right-side since drivers

might have the confusion of the exit location. Thus, the speed difference between the exiting traffic and through traffic on the left-side freeway segments is larger than those at the left-side freeway diverge area. The higher percentage of severe crashes is the main reason that left-side off-ramps can only be allowed under new constructions and should be evaluated carefully.

5.4.3 Crash Predictive Regression Models

A crash prediction models was developed to identify factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of left-side off-ramps and right-side off-ramps at the freeway diverge areas. In this study, only one-lane exits would be considered since the site number for two-lane exits is not adequate enough to develop a generalized linear regression.

A total of 60 sites are included in the final model. The dependent variable of the model is the average number of crashes per year reported at selected freeway segments. Seven variables were initially considered in the model, including number of lanes on the mainline section, speed limit, length of deceleration lanes, ramp length, freeway AADT, ramp AADT and one dummy variable. The dummy variable has two values, 0 represents the one-lane right-side off-ramps while 1 represents the one-lane left-side off-ramps. The crash modeling started from Poisson models.

For an adequate model, the scaled deviance and Pearson's χ^2 divided by the degrees of freedom shall be close to one. These statistics are used to detect overdispersion or underdispersion in the Poisson regression model. Values greater than 1 indicate

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overdispersion, while values smaller than 1 indicate underdispersion. Step-wise regression was used to select the independent variables at a 90% confident level.

Two variables, number of lanes and speed limit, were not found to be statistically significant at the 90% confidence level. The final model contains five variables which are given in Table 18.

Table 18 Poisson Regression Model for One-Lane Left-Side Off-Ramps at Freeway Diverge Areas

Variables	Coefficient	Std. Error	χ^2	Pr $>\chi^2$
Constant	1.0933	0.2172	25.33	<0.0001
Left-side Off-Ramp	0.3996	0.1753	5.21	0.0225
AADT in thousands on freeways in thousands	0.0063	0.0014	20.37	<0.0001
AADT in thousands on ramps in thousands	0.0343	0.0133	6.65	0.0099
Length of the deceleration lane (miles)	0.7181	0.1762	5.37	0.013
Ramp Length (miles)	-0.8232	0.2412	11.64	0.0006
Log Likelihood	274.5123			
SD	53.2472			
Pearson-χ^2	52.5342			
SD/DF	0.98			
Pearson-χ^2/DF	0.97			

The scaled deviance and the Pearson's χ^2 divided by the degrees of freedom is found to be 0.98 and 0.97 respectively. The statistics are reasonably close to one, indicating the fact that the model is adequately fitted. The final equations of the crash models are given as follows:

$$Y_{L1} = \exp(1.0933 + 0.3996X_1 + 0.0063X_2 + 0.0343X_3 + 0.7181X_4 - 0.8232X_5) \quad (33)$$

Where,

Y_{L1} = expected crash frequency in a left-side freeway segment with one-lane exit

ramp (crashes/year);

X_1 = 1 if the exit ramp is left-side off-ramp, 0 if the exit ramp is right-side off-

ramp;

X_2 = mainline freeway AADT for the direction of travel in which the ramp is

located (vehicles in thousands per day);

X_3 = ramp AADT (vehicles in thousands per day);

X_4 = length of the deceleration lane (miles);

X_5 = ramp length (miles);

The coefficients for both freeway AADT and ramp AADT are positive, indicating the fact that the number of crashes increase with the increase of freeway and ramp AADT. The positive sign for the length of deceleration lane indicates that crash counts increase with the increase of the deceleration lane length. This conclusion is not consistent with the results of Bared et al.'s study in which it was found that increasing deceleration lane length will reduce crash frequency; however the results are consistent in this study compared with closely-space diverge areas and widely-spaced diverge areas. Longer deceleration lane lengths might increase more weaving maneuvers at the diverge areas. Further studies are needed to investigate the impact of various deceleration lane lengths on safety.

The only negative sign is the ramp length. It indicates fewer crashes would occur at longer ramp length while all other situations remain same. The conclusion is consistent

with previous study findings (3, 6). The possible reason is might be longer of the length, the less of the distributions from off-ramp traffics.

The coefficient for the indicator variables for left-side off-ramp is positive. It indicates the fact that one-lane exit on the left-side has higher about 49% more total crashes compared to one-lane exit on the right-side .This conclusion is consistent with the results of the cross-sectional comparisons.

5.5 Freeway Exit Ramp Section

5.5.1 Crash Characteristics

Four exit ramp configurations were identified to evaluate their impacts on the safety performance on freeway exit ramp sections. The selected sites were grouped into four categories based on the configurations. For convenience, the four groups were named as D representing the diamond exit ramps with 247 sites, O representing the out connection exit ramps with 93 sites, F representing the free-flow loop exit ramps with 26 sites and P representing the parclo loop exit ramps with 23 sites. A total of 2520 crashes were reported at the selected segments for a three-year period from 2004 to 2006. The average crash frequencies for the four groups are 2.20, 2.32, 2.21 and 1.00 crashes per site per year. Summary of descriptive statistics for four groups are given in Table 19 in terms of crash frequency and crash rate.

Average crash frequency is the mean value of all the crash frequencies in one group at each site for each year. Crash rate is defined in the methodology chapter as crashes per million vehicles per mile. The existing volume was collected at each site. The procedures of calculating the crash rate for each exit ramp site were similar to the diverge

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areas. For example, if one site, A, has 5 crashes for the three years from 2004 to 2006, with the entire ramp length 0.25 miles (1320 ft), and the ADT of 5,000 vehicles per day, then the crash rate for this site A is calculated as follows:

$$R_A = \frac{1,000,000 \times 5}{365 \times 3 \times 5,000 \times 0.25} = 3.65 \text{ crashes per million vehicles per mile} \tag{34}$$

Table 19 Statistical Summary of Four Exit Ramp Configurations

Comparison	Crash Frequency (No. of crashes per year)				Crash Rate (No. of crashes per million vehicles per mile)			
Configuration	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
Mean	2.20	2.32	2.21	1.00	3.47	2.24	5.86	4.88
Std. Error	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

As listed in Table 19, the parclo loop group has the least average crash frequency; however, the out connection group has the best safety performance in terms of the average crash rate among the four groups. For the loop exits, the parclo loop ramp (4.88 crashes per million vehicles per mile) reported 16.7% less crash rate than the free-flow loop ramp (5.86 crashes per million vehicles per mile).

The average crash rate is more reliable as this variable eliminates the impacts of various ramp volumes and ramp lengths. 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. The result indicates that different ramp configurations would affect the ramp safety in different ways. The free-flow ramp need be carefully designed. This conclusion is consistent with previous studies (1, 3, and 5). Also, previous results indicated that the diamond ramps had the best safety performances comparing to other ramp configurations; however, this study shows that the out connection ramps is much safer than the diamond design in terms of the least crash rate.

One possible reason is that this type of exit is widely applied in Florida's highway systems compared to other states so that the sample size is enough to make a reasonable judgment. It is also noticed that the out connection ramp has a higher design standard than other types. These improved standards would provide better sign locations, road pavement conditions and roadway directions along the exit ramps.

Hypothesis tests were used to test whether there is significant difference between the ramp configurations at a 90% confidence level ($t_{0.05}$=1.645). Table 20 lists all the results of the hypothesis tests. If the comparison of the two configurations is significantly different, it shows "YES", otherwise "NO".

For the crash rate, the out connection exit ramps have significant different performance 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 a 90% confidence level. The free-flow ramps have the highest average crash rate and the hypothesis tests proved that this ramp configuration is more dangerous than the diamond ramps and out connection ramps. However, the difference between the free-flow ramps and parclo ramps is not significant.

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Table 20 Statistical Test Results of Overall Crashes for Four Exit Ramp Configurations

Configuration Comparison	D vs. O	D vs. F	D vs. P	O vs. F	O vs. P	F vs. P
Crash Frequency	NO	NO	YES	NO	YES	YES
Crash Rate	YES	YES	NO	YES	YES	NO

5.5.2 Crash Types

Three target crash types that have the three highest percentages of crashes are rear-end crashes, angle crashes and sideswipe crashes. Table 21 lists the statistical summary for the four configurations. Almost half the crashes (50%) occurring on the diamond exit ramps are rear-end crashes while only one-third for the out connection ramps (37%) and parclo loop ramps (35%). The free-flow loop ramp has the least percentage of rear-end crashes (25%) compared to the three types while it does have a highest percentage of angle and sideswipe crashes. This is mainly contributed by the ramp configuration itself. Free-flow loop ramps require drivers change direction at a certain level to keep stable along the ramp curvature. As a result, it would easily to get involved in weaving especially travelling at a relative high speed, thus create more weaving maneuvers. For this type of ramp, the author does recommend that the change of curvature should be gradually and easily for drivers to follow.

Proportionality tests were conducted to compare the percentages of crash types among the four configuration groups. Table 22 lists all the hypothesis test results. If the comparison of the two configurations is significantly different, it shows "YES", otherwise "NO".

The diamond exit ramps have significant higher percentage of rear-end crashes than the other three types at a 90% confidence level ($Z_{0.05}=1.645$); while free-flow loop exit ramps have significant higher percentage of angle and sideswipe crashes than the diamond and out connection exit ramps. But the free-flow loop exit ramps and parclo loop exit ramps did not have significant difference for sideswipe crashes. This conclusion is consistent with the reason mentioned above as loop exit ramps have more opportunities occurring sideswipe crashes due to the curvature changing on the ramp.

Table 21 Statistical Summary of 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
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
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

Table 22 Proportionality Tests of Target Crash Types for Four Exit Ramp Configurations

Configuration Comparison	D vs. O	D vs. F	D vs. P	O vs. F	O vs. P	F vs. P
Rear-end	YES	YES	YES	YES	NO	NO
Angle	NO	YES	NO	YES	NO	YES
Sideswipe	NO	YES	NO	YES	NO	NO

5.5.3 Crash Severity

Summary of crash severity for four ramp configurations are given in Figure 30. The injury/fatal crashes accounted for two-thirds (65%) of the total crashes if the ramps are loop designed while the PDO and injury/fatal crashes are almost equal (55% and 45%) if the ramps are non-loop designed. The results indicate the loop ramps are more dangerous than the non-loop ramps regarding the higher percentage of severe crashes. The conclusion is consistent with the results of target crash types due to the higher percentage of weaving and angle crashes generally more likely to involve in severe crashes.
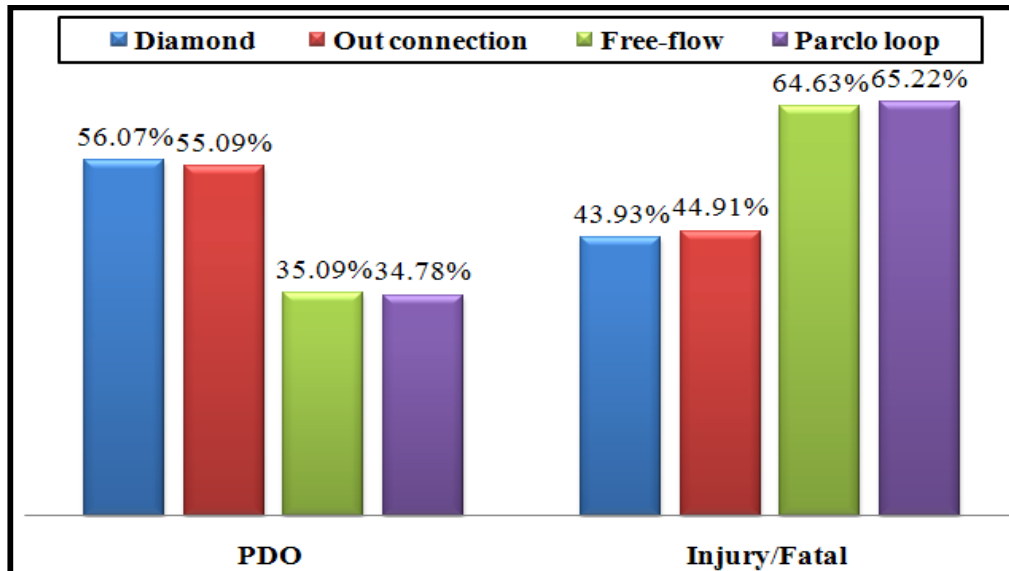
Figure 30 Comparison of Crash Severity for Four Ramp Configurations on Exit Ramp Sections

Proportionality tests were also conducted to test the differences in crash severity among four 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 for the proportionality tests are listed in Table 23. If the comparison of the two configurations is significantly different, it shows "YES", otherwise "NO".

The results imply that the impacts of different ramp configurations on crash severity are statistically significant for the loop exit ramps with non-loop exit ramps. Free-flow loop exit ramps and parclo loop exit ramps have significantly higher percentage of injury plus fatality crashes comparing to diamond and out connection exit ramps at a 90% confidence level. Loop exit ramps are more likely to involve in severe crashes; however, the differences in crash severity between two loop ramps and two non-loop ramps respectively are not significant.

Table 23 Proportionality Tests of Crash Severity for Four Exit Ramp Configurations

Crash Severity	D vs. O	D vs. F	D vs. P	O vs. F	O vs. P	F vs. P
PDO	NO	YES	YES	YES	YES	NO
Injury/fatal	NO	YES	YES	YES	YES	NO

5.5.4 Crash Predictive Models

A crash predictive model was developed to identify the factors that contribute to the crashes reported on selected exit ramp sections. Considering the availability of data resource, a total of 388 sites were included in the final model. One site was excluded from the database as this site did not have the ramp design data.

The dependent variable of the model is the average crash frequency per year reported on selected exit ramp sections. Nineteen independent variables were initially considered to build the crash model. The initially selected independent variables are described in Table 24. 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 χ^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 χ^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.

Table 24 Initially Selected Independent Variables on Exit Ramp Sections

Variable	Min	Max	Mean	Frequency
Out connection exit ramp				388
1 (out connector)				93 (23.97%)
0 (others)				295 (76.03%)
Free-flow loop exit ramp				388
1 (free-flow loop)				26 (6.70%)
0 (Others)				362 (93.30%)
Parclo loop exit ramp				388
1 (parclo loop)				23 (5.93%)
0 (Others)				365 (94.07%)
Number of freeway mainline	2	6	3.6	388
Length of entire ramp (miles)	0.1	1.88	0.38	388
Number of lanes on exit ramps	1	2	1.22	388
AADT in thousands on the ramp	0.2	7.6	1.0	388
Distance to the upstream intersection on the secondary roadway (miles)	0.01	0.97	0.18	388
Distance to the downstream intersection on the secondary roadway (miles)	0.03	0.98	0.22	388
Right shoulder width	6	15	10.08	388

Table 24 (continued)

Road surface condition				388
Widening				388
Post speed on mainline	50	70	64.08	388
Suggested speed on ramp	25	55	36.10	388
Channelization				388
0 (no channelization)				91 (23.45%)
1 (channelization at the ramp terminal)				297 (76.55%)
0 (no widening)				305(78.60%)
1 (widening on the ramp)				83 (21.40%)
0 (Dry)				362 (93.30%)
1 (Wet)				26 (6.70%)
Land type				388
0 (primarily business)				272 (70.10%)
1 (primarily residential)				116 (29.90%)
Road surface type				388
0 (Blacktop)				28 (7.22%)
1 (Concrete)				360 (92.78%)
Right shoulder type				388
0 (Paved)				297(76.55%)
1 (Unpaved)				91(23.45%)
Signal				388
0 (no signal control)				85(21.30%)
1 (signal control at the ramp terminal)				303(78.70%)

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 25 and Table 26.

Table 25 Regression Model Outputs for the Exit Ramp Sections

Analysis of Parameter				
Parameter	Coefficient	Std. error	χ^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
AADT in thousands on ramp	0.2470	0.0860	0.4155	0.0041
Shoulder 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		

As shown in Table 26, the scaled deviance and Pearson's χ^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.

Table 26 Goodness of Fit of Crash Predictive Model for Exit Ramp Sections

Criteria	DF	Value	Value/DF
Criteria for Goodness of Fit			
Deviance	375	441.8539	1.18
SD	375	441.8359	1.18
Pearson χ^2	375	397.9857	1.06
Scaled Pearson	375	397.9857	1.06
Log Likelihood		3221.6867	

The final model is given as follows:

$$Y_E = \exp(-1.0721 - 0.2253X_1 + 0.4392X_2 + 0.2973X_3 - 0.2608X_4 - 0.0062X_5$$
$$+ 0.6861X_6 + 0.3679X_7 + 0.2470X_8 - 0.0978X_9 + 0.0129X_{10} + 0.0580X_{11}) \quad (35)$$

Where,

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

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

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

X_3 = 1 if the site is a 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, 0 no widening;

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

X_8 = ADT in thousands on exit ramp sections;

X_9 = Ramp shoulder width (mile);

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

X_{11} = Suggested speed limit on exit ramp sections (mph);

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 the ramp AADT, the speed limit on mainline sections, the suggested speed on the ramp, 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 width. With the increase of number of lanes on the exit ramp sections, the influence is different from the situation at the freeway diverge areas. The more number of lanes on the ramp sections might diminish vehicle distributions on the ramp sections. The desperation of vehicles would diminish conflict points on the ramp section. While the ramp length is longer, 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. With larger should width, drivers have more flexible spaces while dangerous situations happened. For example, the drivers could have more spaces to avoid angle and sideswipe crashes for loop exit ramps compared to the narrow should width.

The increasing of AADT on the exit ramp sections would increase the opportunities having potential crashes. It is consistent with previous studies. Post speed limits both on mainline have a trend to increase crashes. Mostly the ramp design speed, usually 25 to 40 mph, is much lower than freeway mainline section. Drivers would continually maintain high speed on the ramp section; however 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.

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Another two variables have positive signs are the indicator variable of widening and the continuous variable of 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 occurring 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 of the model can be used to quantify the safety impacts of different exit ramp configurations. Based on the model, only the sign of out connection exit ramp is negative. It can be concluded that replacing a diamond exit ramp with an out connection exit ramp will reduce crashes by exp (0.2253)-1=26.90% while under conditions keep the same. 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% and 48%. 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%. This conclusion is consistent with the results from the cross-sectional comparisons.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The primary objective of the study is to evaluate the safety performance of different design types at freeway diverge areas and freeway exit ramp sections. At the freeway diverge area, three situations are identified, the widely-spaced freeway diverge area, the closely-spaced freeway diverge area and the left-side off-ramp. 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 current the freeway diverge areas and exit ramps.

For the freeway diverge areas, the basic number of lane and the lane balance theory were considered to determine the design types. At widely-spaced diverge freeway diverge area, four different types 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 exits, while Type 3 and Type 4 are two-lane exits. Type 1 is a parallel from tangent single-lane exit ramp. Type 2 is a single-lane exit ramp without 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 326 freeway segments were collected in the State of Florida, 180 sites for Type 1 exit ramps, 68 sites for Type 2 exit ramps, 60 sites for Type 3 exit ramps and 18 sites for Type 4 exit ramps.

For the closely-spaced freeway diverge area, it was found that 7 different types of arrangements are used in the current practical engineering applications based on over 1,000 reviewed aerial photos. However, only three types have the sufficient sample size for further investigation, named as Type A arrangement, Type B arrangement and Type C arrangement. For the type A arrangement, a one-lane entrance ramp is closely followed by a one-lane exit with the 26 sites. Considering the coordination of lane balance and the basic number of lanes, both lane balance theory and the consistency of basic number of lanes are maintained for this particular arrangement.

For the type B and type C arrangements, a continuous auxiliary lane connects the entrance and exit ramps. The only difference between these two arrangements, Type B and Type C, is that a type B arrangement is ended with a two-lane exit while a type C arrangement is ended with a one-lane exit. Both type B and type C arrangements are consistent in terms of the basic number of lanes. Whether they are lane balanced designs depends on the length of the continuous auxiliary lanes. A total of 18 and 22 sites were included in the final database as type B and type C arrangements.

For the left-side off-ramp at the freeway diverge area, this study would examine the two most widely designs left-side off-ramp in Florida, which is Type I - one left-side exit-lanes, with 7 sites and Type II - two left-side exit-lanes with an optional lane, with 4 sites. Type I is comparable to Type 1 design type and Type II is comparable to Type 3 design type at widely-spaced freeway diverge area. For convenience, Type 1 and Type 3 are named as Type I* and Type II* corresponding to the left-side off-ramps for this section.

For the exit ramp sections, the exit ramp configurations were grouped by four 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, 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 time period, from 2004 to 2006 for each site. Cross-sectional comparisons were also conducted to compare the crash frequency, the crash rate, the target crash types and the crash severity among different design types. Rear-end crashes, sideswipe crashes and angle crashes are defined as the target crash types which have the highest percentages of crashes to total crash counts. Crash severity was grouped by two categories, property-damage-only crashes and injury/fatal crashes. The hypothesis tests were conducted between each design types at the 90% confidence level. Crash predictive models were developed to identify the factors that contribute to the crashes reported at selected freeway segments and to quantify the safety impacts of different design types.

6.2 Conclusions

In this study, safety performance of four research subjects, widely-spaced freeway diverge areas, closely-space freeway diverge areas, left-side off-ramps and exit ramp sections, are analyzed separately. The conclusions are drawn for these four parts in the following sections.

6.2.1 Freeway Widely-Spaced Diverge Area

This study evaluated the impacts of the number and arrangement of exit lanes on the safety performance at widely-spaced freeway diverge areas. Four different types of exit ramps were considered in this study, including two one-lane exits and two two-lane exits. The cross-sectional comparison results show that type 1 exit ramp has the best safety performance in terms of the lowest crash frequency and crash rate at freeway diverge areas. As mentioned before, type 1 exit ramp is a single-lane exit with tapered design.

The results of crash data analysis also demonstrated the safety benefits of using lane-balanced exits. The t-test results show that lane-balanced exit ramps have significantly lower crash counts and crash rates as compared to those not lane balanced. In this study, type 1 and type 3 exits are lane-balanced while type 2 and type 4 are not lane balanced. Both type 2 and type 4 exits have a freeway mainline dropped at the exit gore. Field observation showed that the dropped lane could, sometimes, trap drivers at the exit gore. This may result in more crashes at freeway diverge areas. However, the differences between crash severity and three target crash types are found not be statistically significant.

Crash prediction models were further developed to identify factors that contribute to the crashes reported at selected freeway segments. It was found that the length of the deceleration lane, posted speed limit on freeway, right-shoulder width on freeway, the mainline freeway AADT and ramp AADT, and whether exit ramps are lane balanced significantly affected crashes at freeway diverge areas. The crash prediction models can also be used to quantify the safety benefits of using lane-balanced exits. Based on the

crash prediction models, replacing a type 1 exit ramp (lane balanced) with a type 2 exit ramp (not lane balanced) will increase crash counts at freeway diverge areas by 68.47%. Replacing a type 3 ramp (lane balanced) with a type 4 ramp (not lane balanced) will increase crash counts at freeway diverge areas by 31.18%.

Currently, the number and arrangement of lanes used by traffic to exit freeways is mainly determined based on freeway and ramp traffic demand. The safety impacts of different types of exit ramps have not been fully considered. The results of this study provide a method for quantifying the impacts of different exit ramp types on the safety performance of freeway diverge areas. Designers can also use the crash models to evaluate the safety impacts of various explanatory variables such as the freeway AADT, ramp AADT, deceleration lane length, and right shoulder width, etc. The research results have the propensity to help transportation decision makers develop technical guidelines governing the selection of the optimum exit ramp types to be used on our freeways.

6.2.2   Freeway Closely-Spaced Diverge Area

The objective is to evaluate how lane arrangements on freeway mainlines and ramps affect safety of freeways with closely spaced entrance and exit ramps. To negotiate the principles of lane balance and the consistency in the basic number of lanes, three most frequently used were designated as type A, type B and type C arrangements.

The crash data analysis results show that the type C arrangement has the lowest average crash frequency and crash rate. Crash severity analyses show that freeway segments with type A arrangements reported the lowest percentage of injury/fatal crashes. Freeway segments with type B arrangements reported the highest average crash

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frequency, average crash rate, and percentage of injury/fatal crashes. The type A arrangement is considered as the desirable type at freeway diverge areas since most of the crashes are rear-end crashes generally not resulting in severe consequences. As mentioned before, freeway segments with type B arrangements are designed with continuous auxiliary lanes which connect the entrance and exit ramps; and the auxiliary lanes are dropped in two-lane exits. Crash data analysis results suggest that the type B arrangement should be used cautiously when entrance and exit ramps are closely spaced.

Crash prediction models were developed to relate the crash counts reported at selected freeway segments to various explanatory variables such as traffic conditions and geometric characteristics. With the crash prediction models developed in this study, one can compare the safety performance of different lane arrangements by taking into account the impacts of various external factors.

Two predictive models, one for the total crash counts one for severe crash counts, were developed. The best total crash model has 6 independent variables plus an interaction term. The independent variables include the freeway mainline ADT, the number of lanes on mainlines, logarithm the entrance ramp ADT, an indicator variable for the posted speed limit on freeway mainlines, and two indicator variables for the type of arrangements. The severe crash model contained four variables, the number of lanes on freeway mainlines, the logarithm of entrance ramp ADT, the posted speed limit on freeway mainlines and one indicator variable for the Type B arrangement.

Based on the crash prediction models, if other factors remain constant, a type A arrangement will result in exp (0.379)-1=46% more total crashes than does a Type C arrangement. Similarly, a type B arrangement will result in 113% more total crashes and

102% more severe crashes as compared to a type C arrangement. Again, the crash prediction models indicate the same results with the cross-sectional comparison. When considering the design types at the close-spaced diverge area, even a type C arrangement might have lower crash counts compared to other types, it is still benefit to consider the Type A arrangement in terms of the least percentage of severe crashes. The Type B arrangement is not recommended for the new design in terms of the highest number of total crashes and percentage of severe crashes.

6.2.3   Left-Side Off-Ramp

To evaluate the effects of exit ramp locations on safety, two types of left-side off-ramps were collected and analyzed. Crash records were analyzed at 74 sites on freeways, including 7 sites for Type I (one-lane left-side off-ramp), 53 sites for one-lane right-side off-ramp (Type I*), 4 sites for two-lane left-side off-ramp (Type II), and 10 sites for Type II* (two-lane right-side off-ramp with an optional lane).

Cross-sectional comparisons were conducted to evaluate the safety performance of left-side off-ramps at freeway diverge areas. The comparisons indicate that the left-side off-ramp did have higher average crash counts, crash rate and percentage of severe crashes, but the difference is only statistically significant for the severe crashes. The results indicate the side of exits is not the main causation of the overall crashes, but the severe crashes.

A crash prediction model for one-lane exit was developed to identify the factors that contribute to the crashes that have been reported for selected freeway segments. Increasing the freeway AADT, ramp AADT or length of deceleration lane, would

increase the overall crash counts while increasing the ramp length would reduce the potential crash counts for both left-side and right-side diverge areas.

This study investigate the engineering confusion of the safety performance on-left-side diverge segments. The main reason that left-side off-ramps, which only can be allowed under new construction, are always critical issues is because of the significant higher severe crashes than the similar right-side off ramps at freeway diverge area. The author recommend further countermeasures could be focused on reduce the potential severe crashes on the left-side diverge segments.

6.2.4   Exit Ramp Section

Four exit ramp configurations were identified to evaluate their impacts on the safety performance on freeway exit ramp sections. The selected sites were grouped into four categories based on the configurations, the diamond exit ramps with 247 sites, the out connection exit ramps with 93 sites, the free-flow loop exit ramps with 26 sites and the parclo loop exit ramps with 23 sites.

The comparison of history crash data indicate the out connection exit ramp has the best safety performance in terms of lowest crash rate. Diamond exit ramps have significant higher percentage of rear-end crashes than the other three types; while free-flow loop exit ramps have higher percentages for angle and sideswipe crashes than the non-loop exit ramps. Statistical tests proved that the loop exit ramps have significant higher percentages of severe crash than non-loop exit ramps at the 90% confidence level. This is mainly contributed by the ramp configuration itself. Loop designed ramps require drivers change direction at a certain level to keep stable along the ramp curvature. As a

result, it would easily to get involved in weaving especially travelling at a relative high speed, thus create more weaving maneuvers which generally result in severe consequences. For this type of ramp, the author does recommend that the change of curvature should be gradually and easily for drivers to follow.

The crash predictive model was developed for total crash counts at selected 388 sites. The final model included eleven independent variables. The crash counts at exit ramp sections increase with the increasing of ramp AADT, speed limit on mainline sections, suggested speed on ramp sections, distances from ramp terminals to the first upstream intersection, or widening at the exit ramp, but decrease with the increasing of ramp length, the exit ramp lane number and ramp shoulder width.

From the model, it is also noticed that the out connection exit ramp has the best safety performance. 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% respectively. For the loop exit ramp, replacing a parclo loop exit ramp with a free-flow loop exit ramp would increase crash counts by 15.60%.

6.3 Practical Guidelines to Implement the Study Results

One of the major purposes of this study is to provide the decision-makers, engineers, and researchers a better understanding of the safety performance by current practical designs at freeway diverge areas. The results of this study aim to help the designers to select the optimum exit types under various geometric, traffic and other conditions in the future designs and choose the appropriate countermeasures for current

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exits to reduce potential crashes, thus improve the safety performance. The following

Table 27 is provided in addition to assist the potential users by applying the study results.

Table 27 Overall Design Guidelines under Different Design Conditions

Study Subject	Optimal Exit Types	Potential Countermeasures Focus
Widely-Spaced Diverge Areas	➤ For one-lane exit, the deceleration lane is desirable for both parallel or taper design types; ➤ The deceleration lane length should not be too long to trap vehicles use it as a general purpose lane; ➤ For two-lane exits, an optional lane is desirable; ➤ Direct lane drops are not recommended in future designs, especially for two-lane exits; ➤ Wider shoulder width is preferred;	➤ Provide better advance signs both before and after the lane drops; ➤ Widen right shoulder width; ➤ Provide an optional lane for two-lane exits if possible;
Closely-Spaced Diverge Areas	➤ For one-lane entrance and one-lane exit, an auxiliary lane is not desired compared to one-lane entrance and one-lane exit without an auxiliary lane; ➤ If an auxiliary lane is necessary, countermeasures should be provided to reduce potential severe crashes; ➤ One-lane entrance followed by two-lane exits are not recommended;	➤ Focus on reducing severe crashes for one-lane entrance and one-lane or two-lane exits with an auxiliary lane; ➤ For two-lane exits, a better sign improvement is necessary;
Left-Side Off-Ramps	➤ Left-side off-ramps should be avoided in future designs; ➤ If this design type is necessary, it should be carefully selected and provide sufficient distance for vehicles make consequent maneuvers to exit freeways;	➤ Geometric improvement before the exits is wanted to provide both familiar and unfamiliar drivers enough reaction time to change lanes; ➤ Sign improvements;
Exit Ramp Sections	➤ Non-loop exits are recommended compared to loop designs, especially out connection designs; ➤ Widening on the ramps is not recommended unless signs are clearly provided before the widening; ➤ Wider shoulder width is preferred;	➤ Focus on reducing potential crashes and severe crashes for the loop designs; ➤ Provide signs if widening exits;

6.4 Limitations and Future Studies

The following limitations shall be considered when the results of this study are to be applied. Firstly, the crash database used in this study is based on police-reported crashes. Unavoidably, the data is associated with certain levels of mistakes. This is particularly true for the crash locations which are estimated by police officers based on the mile markers on freeways.

The second limitation is the application of the cross-sectional comparison method. In essence, traffic safety studies are observational studies. Researchers cannot fully control the external factors that affect safety, and the information about crashes is often incomplete. Some factors, such as the factors related to human behaviors, are usually hard to measure and their impacts on crash analysis results are often not clear. To minimize the limitations of cross-sectional comparison methods, the current best method is to use before-after studies which can be conducted after a particular type of exit ramp was replaced by another type. If enough sites and crash data can be found, before-after studies can be a good supplement to the present study.

The third limitation is associated with the generalized linear regression models. The purpose of modeling the crash frequency is to find the contributing factors to the crashes occurring at the selected freeway segments and quantify their effects. From this aspect, the decision to select the explainable variables is based on how the variables can practically represent the geometric features and traffic conditions. These variables should be easily interpreted and controller by the designers, traffic engineers and decision makers. For example, this study chose the post speed limits as the explainable variables both in the total crash counts model for widely-spaced diverge areas and closely-spaced

diverge areas. The regression results indicate that a higher speed limit would result in fewer crashes if all others remain same. The author notices that the possible reason might because of a higher post speed limit relating to better traffic surroundings, better signing, lighting, pavement designs, or different land use types. As a result, the selection of the final model is also determined by the significance and usefulness of these variables for future designers besides the Pearson χ^2 and SD vales.

Note that the crash prediction models developed in this study were only used to compare the safety performance of different design types. To select the optimal design type, the author recommends that the following study areas need further investigate:

1) The operational effects are not considered in this study. In reality, when selecting the optimal design type, the operational performance such as the capacity of the weaving segment is also an important consideration. Operational impact and safety impacts should look closely to determine the practical design for both freeway diverge areas and exit ramp sections.

2) Another important consideration is the conflict studies on these sites to further refine the results. With the research results of this study and the conflict analysis designers can make design decisions by joint consideration of the safety and operational effects of the freeway segments with different types of lane arrangements on mainlines and ramps.

3) Drivers' behavior is another important factor when deciding the optimal design type among different study area.

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ABOUT THE AUTHOR

Ms. Hongyun Chen is currently a Ph.D. candidate in civil engineering with a concentration in transportation at the University of South Florida (USF). She got her B.S. in harbor, channel and coast engineering in 2006 and M.S. in civil engineering in 2008. Her career goal is to become a leading researcher and an inspiring teacher in the field of transportation engineering. She has been working as a graduate research assistant at the Center for Urban Transportation Research (CUTR) since 2007. Her research interests focus on transportation safety and operation, highway geometric design, traffic simulation, Intelligent Transportation Systems (ITS), and statistical modeling in transportation. She served as the president of USF ITE student chapter for the 2008-2009 academic year and has been involved in several professional associations. She was also the recipient of 2010 Georgia Brosch Memorial Transportation Scholarship in 2010. Her research work has been presented at several national and international conferences.