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Operational Performance Evaluation of Four Types of Exit Ramps on Florida's Freeways

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Four Types of Exit Ramps on Florida's Freeways

by

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TSIS-CORSIM, Simulation

Dedication

I dedicate this dissertation to my family and friends, especially …

To my parents for opening my eyes to the world,

To Dr. John Lu for his guidance and teaching,

To Jane Zhang for her love and care,

To Pan Liu, Tao Pan, Qing Wang, Bin Cao, Changjiang Zheng, Lei Zhang, and all other colleagues for their assistance of this project, and

To all saints in Tampa Local Church who helped me with my life.

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The contents of the report reflect the views of author, who is responsible for the facts, opinions, and accuracy of the information presented here. The contents do not necessarily reflect official views or policies of the sponsoring agency.

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Abstract

This research focuses primarily on the analysis of exit ramp performance related to safety and operations. The safety analysis focuses on the impacts of different exit ramp types for freeway diverge areas and different factors contributing to the crashes that occur on the exit ramp sections. The operational analysis is based mainly on simulations by TSIS-CORSIM. Different ramp effects and guidance for selecting optimal exit ramp type are concluded. Issues related to ramp sections and crossroad sections are also demonstrated. Minimum ramp length and minimum distance between ramp terminal and downstream or upstream intersections are calculated. The operational analysis was conducted to determine different ramp effects and to provide guidance for selecting optimal exit ramp type.

Comparisons of the operational performance of different types of exit ramps are made to present a method for choosing the optimal one. Some methods of evaluation (MOEs) are used to approach this objective, such as number of lane changes, average speed, delay time, etc. Data collection at 24 sites in Florida was conducted, and traffic simulations by TSIS-CORSIM were applied for analysis. Mathematical models were built to evaluate different impacts of these ramps based on simulations. All impact analysis is concluded to summarize a model for optimal exit ramp selection. In addition to ramp type evaluation and selection, issues related to ramp section and

crossroad section are demonstrated. Minimum ramp length and minimum distance between ramp terminal and downstream or upstream intersections are calculated.

Chapter 1 Introduction

1.1 Background

In Florida, several types of exit ramps are used for traffic to exit freeways (i.e., Interstate and Turnpike systems). Drivers exiting freeways need to make decisions and execute maneuvers (i.e., lane change or lane merge) prior to the exit ramp in order to access crossroads at interchanges. If the exit ramps are not sufficiently long, drivers must complete their driving maneuvers within a short distance, resulting in potentially unsafe driving actions (i.e., fast-paced deceleration, lane changing, merging, unbalanced lane utilization, etc.), which will result in the development of shock-waves on upstream traffic, etc. Considering these factors, there are several issues and concerns that need to be addressed in selecting the optimum types of freeway exit ramp(s) to use at a given interchange.

Some of these concerns include, but are not limited to, the operational performance and correlation between types of exit ramps, lane utilization, geometrics, land use along the crossroad, adequate distances for lane change, deceleration, and adequate distance for traffic to transit from the exit gore to the downstream intersection, which includes weaving. These issues have not been studied in the past, and no clear guidelines, either federal (AASHTO Green Book) or state, are currently available in selecting exit ramp types. Therefore, there is a need to perform research under Florida conditions to specifically evaluate the operational performance for each exit ramp type to develop tailored guidelines that address the issues.

This need is especially significant considering the rapid increase in new developments close to freeway interchanges. The Florida Department of Transportation (FDOT), in joint cooperative efforts with local land use agencies, can use the findings of this research to determine the type of exit ramps that should be constructed at a given location considering the prevailing conditions applicable to traffic, roadway, and land use developments.

1.2 Research Objectives

The main goal of the research is to develop tailored technical guidelines governing the selection of optimum exit ramp types to be used on Florida freeways. Typical exit ramp types include, but are not limited to, single-lane exit ramp with a taper, single-lane exit ramp without a taper, two-lane exit ramp with an optional lane, and two-lane exit ramp without an optional lane (see Figures 1.1 to 1.4).

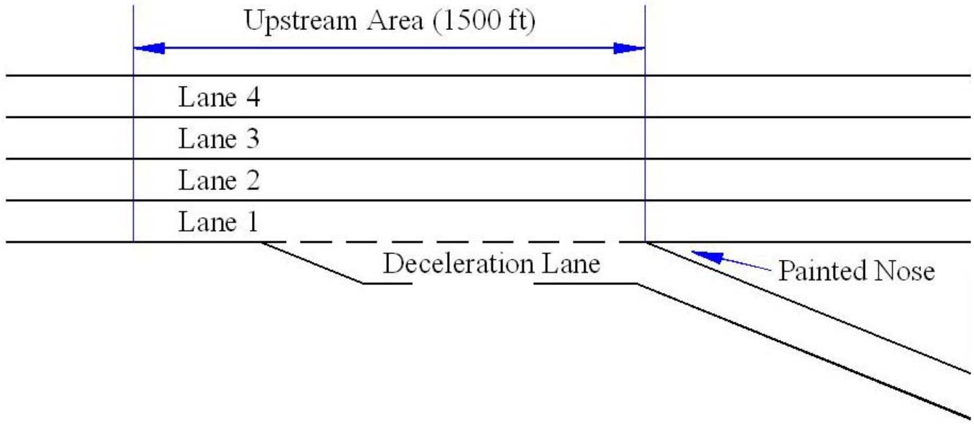

Figure 1.1 Type 1 single-lane exit ramp with a taper

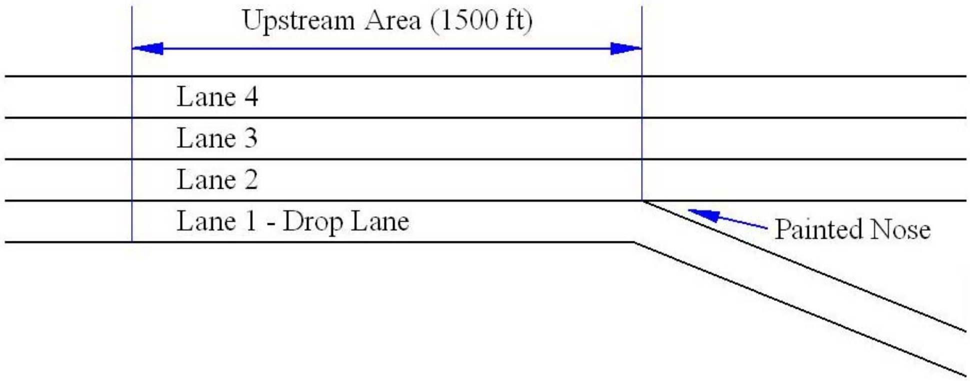

Figure 1.2 Type 2 single-lane exit ramp without a taper

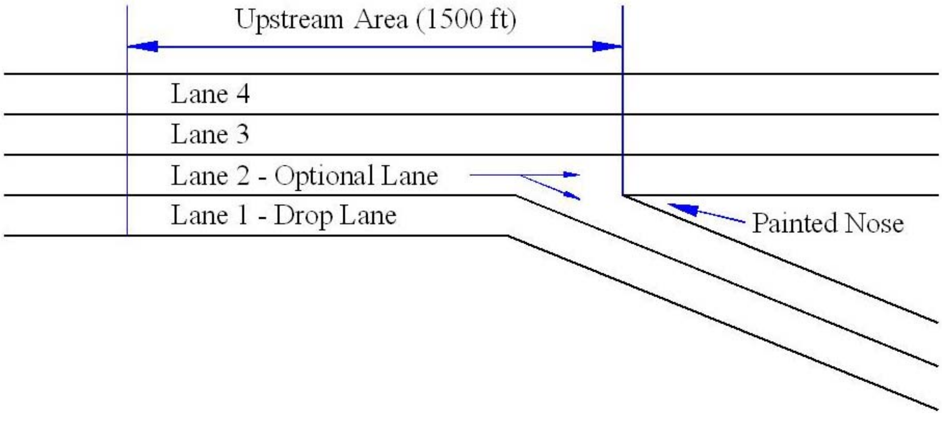

Figure 1.3 Type 3 two-lane exit ramp with an optional lane

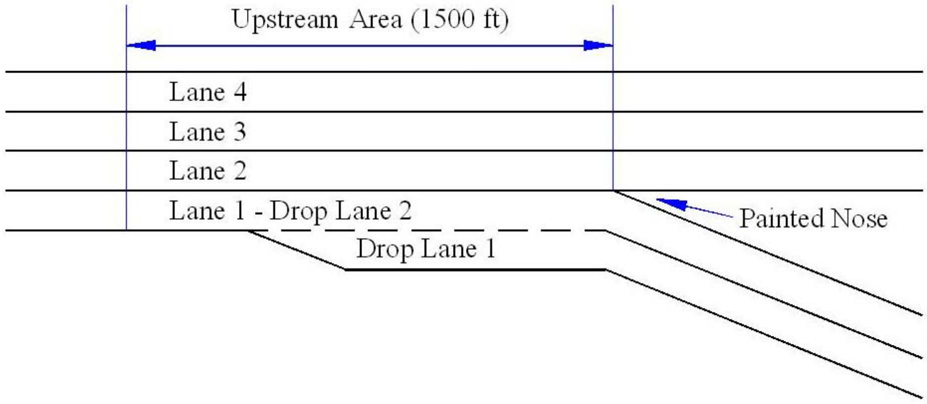

Figure 1.4 Type 4 two-lane exit ramp without an optional lane

Another objective is to present some design guidelines, such as ramp length design, ramp curve design, super elevation design, minimal distance design on cross road, etc., which are also based on operational analysis.

A survey was conducted to investigate the distribution of different types of exit ramps in the state of Florida. Table 1.1 shows that more than 95% exit ramps are of these four selected types. Thus, the research on these four typical exit ramp types is very significant to Florida Highway system.

Table 1.1 Exit ramp type survey

Interstate Highway	Length (mile)	Type 1	Type 2	Type 3	Type 4	Other	Total
I-4 (Primary)	133	59	32	29	2	5	127
I-275 (Auxiliary)	64	35	14	6	1	2	58
I-295 (Auxiliary)	36	39	12	5	3	0	59

All the analysis is based on a traffic operational performance evaluation. Video cameras were installed at selected sites to record vehicle movements so that performance data such as delay, operating speed, number of necessary or unnecessary lane changes/merges, lane utilization, vehicle queue length, level of service, capacity, etc., could be obtained for each exit ramp type. After capture the existing data of exit ramps, the simulation software TSIS (Version 6) was used to change possible variables to simulate different traffic, geometric, and control conditions.

1.3 Sections of Exit Ramp

The analysis of exit ramps includes three main sections: freeway section, ramp section, and crossroad section (see Figure 1.5). A freeway section refers to the upstream section of an exit ramp on a freeway, whose length is 1500 ft, which is generally considered the impact distance of an exit ramp. Exit ramp section is from the start point of the ramp, the painted nose, to the end of the ramp, the ramp terminal. If there is a left or right taper at the ramp terminal, the end of the ramp is the point where the taper intersects the crossroad. A crossroad section is started from the downstream intersection of the ramp terminal to the upstream intersection of the terminal. All data for these two intersections were included in this area.

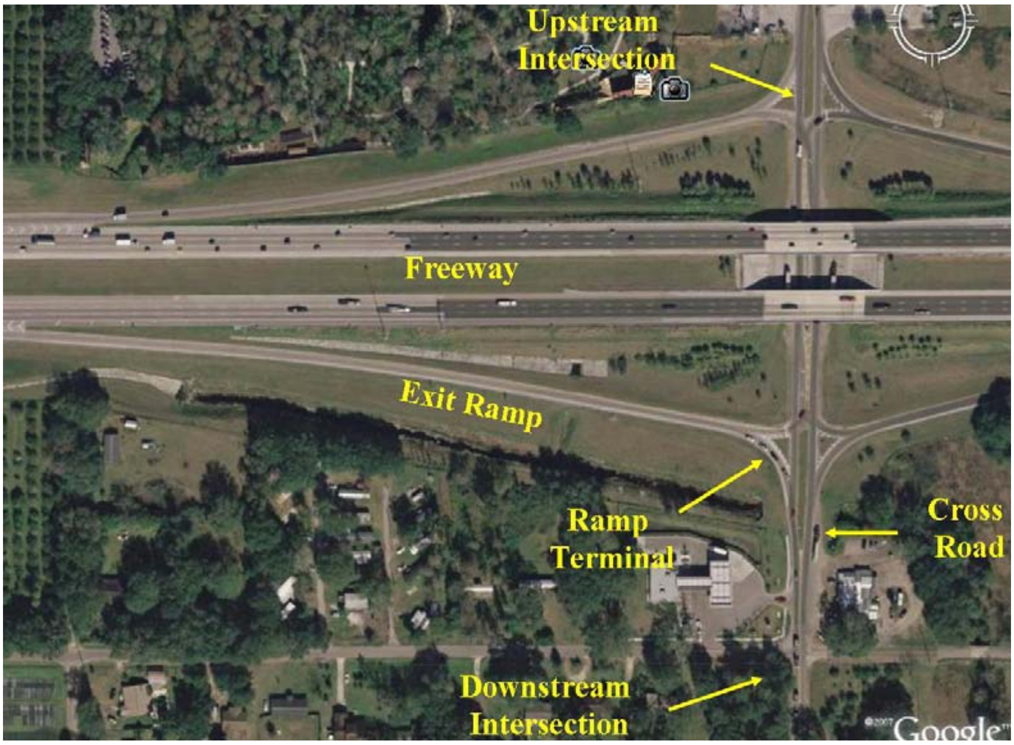

Figure 1.5 Main sections for analysis

Chapter 2 Literature Review

Previous studies and findings of the operational performance on freeway diverge areas, exit ramps, and crossroad sections are reviewed and summarized in this chapter. The freeway is one of the primary components of a transportation network and is categorized as the highest functional hierarchy of the highway system. The grand reliance on this facility promotes the essence of applying a reliable, efficient, and sustainable infrastructure system; thus, the operational performance is obviously an important consideration in freeway exit ramp design. Many factors are related to operations on freeways and their adjacent facilities. The wide variety of site geometric conditions, traffic volumes, ramp types, and design layouts could increase or decrease operation levels.

2.1 Previous Findings

Al-Kaisy (1978) used a simulation approach for examining capacity and operational performance at freeway diverge areas. Freeway diverge areas, and particularly those in the proximity of exit ramps, are often viewed as potential bottlenecks in freeway operations. The existing diverge procedures within the 1994 and 1997 *Highway Capacity Manual* updates are limited in that they do not provide a direct estimate of freeway capacity, nor do they model performance at oversaturated traffic conditions. Moreover, a parallel investigation of these procedures revealed some inconsistencies in predicting measures of performance at those critical areas. This paper describes the use of computer traffic simulation to explore the patterns of capacity and operational performance behavior at these areas under the impact of some key geometric and traffic variables. For this purpose, the microscopic traffic simulation model INTEGRATION was selected to conduct an extensive experimental work on a typical ramp-freeway diverge section. Five control variables were investigated, namely, total upstream demand, off-ramp demand, length of deceleration lane, off-ramp free-flow speed, and number of lanes at mainline. The impact of upstream or downstream ramps was considered beyond the scope of this research. Except for off-ramp free-flow speed, the impact of other control variables on capacity and operational performance was shown to be significant. Also, the simulated trends of traffic behavior showed considerable agreement with logic and expectations in light of the current state of knowledge on freeway operations.

Cassidy et al. (2000) conducted research on freeway traffic near an exit ramp. He assumed that the freeway section near an exit ramp is a bottleneck. A bottleneck with a diminished capacity is shown to have arisen on a freeway segment whenever queues from the segment's off-ramp spilled over and occupied its mandatory exit lane. Although the ramp's queues were confined to the right-most exit lane, non-exiting drivers reduced their speeds upon seeing these queues, which diminished flows in all lanes. It was also shown that the lengths of these exit queues were negatively correlated with the discharge flows in the freeway segment's adjacent lanes, i.e., longer exit queues from the over-saturated off-ramps were accompanied by lower discharge rates for the non-exiting vehicles. Whenever the off-ramp queues were prevented from spilling over into the exit lane (by changing the logic of a nearby traffic signal), much higher flows were sustained on the freeway segment, and a bottleneck did not arise there. These observations underscore the value of control strategies that enable diverging vehicles to exit a freeway unimpeded.

Newell (1998) studied the delays caused by a queue at a freeway exit ramp. This occurs when a queue from an exit ramp backs onto the freeway, causing a partial blockage of the right lane. Exiting vehicles are confined to the right lane but thru vehicles can travel in any lane. The two vehicle types interact, but their queues must be treated separately. This illustrates a special case of a model of "freeways with special lanes'" formulated by Daganzo (1997). Whereas Daganzo presented a numerical scheme of calculating flows, the emphasis here is on graphical evaluation of the complete evolution of the queues. The graphical solution more clearly illustrates the practical issues.

Anon (1976) focused on the design and control of freeway off-ramp terminals, evaluating a more successful design and operating practices used at freeway exit-ramp terminals and concluded that the design of exit ramps should be related to both the freeway and the crossroad. Grades should be as flat as possible and, where possible, the entire ramp should be visible from the freeway exit. The ramp should have a relatively flat platform at the intersection with the crossroad. Adequate stopping sight distance must be provided throughout the length of the ramp, and enough sight distance is needed at the intersection to allow for safe turns. These suggestions can improve safety performance significantly.

Xiao (2007) studied the minimum-length-requirement model for expressway off-ramp joint. To augment the capacity of off-ramp joint, a method to calculate its length is needed. With the definition and basic hypothesis of off-ramp joint, the characteristic of its structure and traffic flow are analyzed. From a systematic viewpoint, kinematics, gap-acceptance theory, and probability theory were employed to establish the minimum-length-requirement model for expressway off-ramp joint. While modeling, the more difficult traffic maneuver of running off the off-ramp road, finishing its interweaving, and running onto the left-turn lane of downstream intersection were taken into consideration comprehensively. For a newly constructed road, the required minimum length can be computed using the model. For an existing road, based on the comparison of the measured value and calculated value, the model is helpful for determining the reasons for congestion on the off-ramp joint and taking corresponding improvement measures. Finally, the model was verified to be feasible through comparison with the simulation results of CORSIM (corridor simulation model).

Li (2007) did research about factors influencing free flow speed on expressway. In order to research the pattern of the free flow speed (FFS) on the expressway, the measured FFS, the theoretical FFS and the 85 percentile speed and their correlation were analyzed statistically using the traffic data acquired by the loop vehicle detectors buried in the expressway in Shanghai. The attention was focused on the measure FFS, and the regression models between it and the radius of the horizontal curve, between it and the distance to the inlet or from the exit ramp, and between it and the traffic saturation degree. On this basis, a model was presented to estimate the FFS on the expressway without the need of the field data, providing a base for evaluating the service level of the expressway operation system and estimating its traffic flow capacity.

Bunker (2003) predicted minor stream delays at a limited priority freeway merge. He discussed the development and application of a limited priority gap acceptance model to freeway merging. In the limited priority model, drivers in the major stream at a merge area may incur delay in restoring small headways to a larger, sustainable minimum headway between them and the vehicle in front. This allows minor stream drivers to accept smaller gaps. The headway distributions are assumed to be distributed according to Cowan's M3 model, whose terms were calibrated for this system. Minor stream minimum follow-on time was calibrated, and a realistic range of the critical gap identified. An equation was developed for minimum average minor stream delay.

A function was identified to model the relationship between minor stream average delay and degree of saturation. The shape parameter of this function was calibrated using simulated traffic flow data, under three different minor stream arrival pattern regimes. The model provides a useful means of comparing performance, through average minor stream delay, for varying minor and major stream flow rates and minor stream critical gap, under arrival patterns that differ due to traffic control upstream of the on-ramp. Minor stream delay is a particularly useful measure of effectiveness for uncongested freeway merging as it relates directly to the distance required to merge. Observations from the model developed provide physical evidence that minor stream drivers incur lesser delay, or have a better chance of merging quickly, when they arrive at constant intervals as is the case under constant departure ramp metering, than when they arrive in bunches downstream of a signalized intersection, or even a semi-bunched state downstream of an unsignalized intersection.

Zhou (2008) developed a methodology to evaluate the effects of access control near freeway interchange areas. Access connections and signalized intersections within the functional area of an interchange can adversely impact safety and operations at the interchange crossroad and on the freeway, and can cause the interchange to fail prematurely. Standard practice is to acquire a minimum of 90 m (300 ft) of limited access right-of-way beyond the end of the acceleration/ deceleration lanes for rural interchanges and 30 m (100 ft) in urban areas.

His study methodology included the following basic steps: (1) traffic operations analysis of the study interchange with varying configurations of signalized access spacing using CORSIM; (2) safety analysis of a sample of Florida interchanges with varied access spacing; and (3) cost/benefit analysis of acquiring varying amounts of limited access right-of-way. This study indicates that the long-term safety, operation, and fiscal benefits of purchasing additional limited access right-of-way at interchange areas greatly exceeds the initial costs. The findings suggest that state transportation agencies and the traveling public may benefit greatly by an increase in the amount of limited access right-of-way at interchange areas to a minimum of 180 m (600 ft) and a desirable 400 m (1320 ft). Although the safety and operational benefits of managing access in freeway interchange influence areas are clear, the cost effectiveness of purchasing access rights at the time of interchange construction has not been established through national- or state-level research. The primary objective of this study was to assess the relative costs and benefits of purchasing additional limited access right-of-way at the time of construction in lieu of retrofitting interchange areas after functional failure.

2.2 Summary

Exit ramp is always an important research focus, such as ramp capacity, waving area operations, ramp configuration, crash analysis on freeway and ramps, and etc. And previous research findings had already shown some results of such analysis. However, specific analysis on operational performance of different types of exit ramps hasn't conducted yet. Therefore, possible results and conclusions of this research are very helpful for exit ramp evaluation and selection, as well as some geometry design issues.

Chapter 3 Methodology

This chapter mainly describes the methodology of this project, including a microscopic traffic simulation technique, statistical modeling, and some design issues. The main contents consist of introduction to simulation, simulation procedures, freeway section evaluation, ramp parameter design, cross road access spacing, etc.

3.1 Computer Simulation

All operational analysis was based on traffic simulation software TSIS-CORSIM. TSIS can satisfy all the requirements of this project. After data validation and calibration, variables were changed in TSIS to simulate different traffic situations, which saved much energy and time. All collected data were input to TSIS for simulation, and output data provided analysis results for further calculation and comparison.

The Federal Highway Administration’s (FHWA) Traffic Software Integrated System (TSIS) is an integrated development environment that enables users to conduct traffic operations analysis. Built using component architecture, TSIS is a toolbox that contains tools that allow the user to define and manage traffic analysis projects, define traffic networks and create inputs for traffic simulation analysis, execute traffic simulation models, and interpret the results of those models (Figure 3.1).

TSIS is microscopic traffic software with a long history, which guarantees reliability and practicability. The history is as follows:

- Mid 1970s: UTCS-1 (Urban Traffic Control System)
- Mid 1980s: NETSIM
- Late 1980s: TRAF-NETSIM
- 1990: TSIS/NETSIM
- 1994: TSIS/FRESIM
- 1995: TSIS/CORSIM (DOS version)
- 1997: TSIS/CORSIM (Windows version)

Figure 3.1 TSIS interface

TSIS is a complete software package, and different individual tools are included. Each tool has its exclusive function. Here are 10 main components in TSIS Version 6 and their use, which can help better understand how TSIS works, as described below:

- TShell: TShell is the graphical user interface for the TSIS integrated development environment. It provides a project view that enables you to manage your TSIS projects. It is also the container for the pre-configured tools and any tools that you add to the suite. See the TShell User's Guide for additional details.

- TSIS Next: TSIS Next contains the same type of functionality that can be seen in the TShell, TRAFED, and TextEditor component programs. TSIS Next is a “quicker-and-easier” version of TSIS that contains specific advantages and disadvantages. Certain advanced CORSIM applications will continue to require TShell and TRAFED. By having access to both TSIS and TSIS Next on the same computer, you can choose whichever functionality you prefer.
- CORSIM: The CORSIM simulation consists of an integrated set of two microscopic simulation models (NETSIM and FRESIM) that represent the entire traffic environment as a function of time. NETSIM represents surface-street traffic and FRESIM represents freeway traffic. Microscopic simulations model the movements of individual vehicles, which include the influences of driver behavior. Thus, the effects of very detailed strategies, such as relocating bus stations or changing parking restrictions, can be studied with such models. CORSIM provides its own interface in TSIS 6 that enables you to control the simulation and the accumulation of traffic measures of effectiveness. See the CORSIM User's Guide for additional details.
- TRAFED: TRAFED is a graphical user interface-based editor that allows you to easily create and edit traffic networks and simulation input for the CORSIM model. See the TRAFED User's Guide for additional details.

- TRAFVU: TRAFVU (TRAF Visualization Utility) is a graphics post-processor for FHWA's CORSIM microscopic traffic simulation system. TRAFVU displays traffic networks, animates simulated traffic flow operations, animates and displays simulation output measures of effectiveness, and displays user-specified input parameters for simulated network objects. See the TRAFVU User's Guide for additional details.
- TSIS Text Editor: This editor is a standard text editor that has the additional capability of "understanding" the CORSIM TRF file format. When editing a TRF file with this editor, the TShell output window displays text describing the entry field and record type at the current cursor position. Clicking a specific field description in the output window highlights the corresponding entry field in the displayed TRF file. This makes manual editing of the text file much easier than with previous text editors. See the TSIS Text Editor User's Guide for additional details.
- TSIS Script Tool: The TSIS Script Tool is a combined script editor and tool for executing Visual Basic Scripts. Using the built-in TSIS interfaces, the Script Tool is a powerful mechanism for extending the functionality of the other TSIS components. We have also included two scripts with this release. One is a multi-run script that repeatedly runs CORSIM on a test case, applying different random number seeds to each run. The other script runs CORSIM on many different test cases. See the Script Tool User's Guide for additional details.

- TSIS Translator: The TSIS Translator converts TRF files for use by TRAFED. This translator also performs the reverse operation of translating the TRAFED native format (TNO) files into TRF files for use by CORSIM and other tools. See the Translator User's Guide for additional details.
- TSIS Output Processor: The TSIS Output Processor enables the user to automatically compute selected statistics and summary data during multiple runs of CORSIM. The collected data is written to an Excel workbook, a comma-separated file, an XMLtagged file, or a tab-separated text file. The Output Processor can also compute 95th percentile confidence intervals, and can recommend sample sizes (i.e., the number of simulation runs that should be performed with varying random number seeds) for achieving desired accuracy. The Output Processor has been redesigned for TSIS 6 to efficiently summarize any model result generated by CORSIM. Cumulative MOEs may be obtained from the start of simulation, or just for the current time interval, or just for the current time period, or any combination of those three.
- CORSIM Runtime Extension (RTE): Although it comes pre-configured with a set of tools, TSIS provides a mechanism by which an external application can interface directly with CORSIM simulation. This type of application has become known as a CORSIM run-time extension (RTE). Run-time extensions can be built to replace existing logic in CORSIM, or to supplement the logic. The original run-time extensions were tailored for signal timing studies. However, the concept has been expanded to support freeway monitoring,

incident detection, ramp metering run-time extension packages, work zone control, and signalization.

TSIS-CORSIM has a very strong capability with many applications, some of which are related to this project: Freeway and surface street interchanges, Signal timing and signal coordination, Freeway weaving sections, lane adds and lane drops, Ramp metering and HOV lanes, Queuing studies involving turn pockets and queue blockage, etc.

TSIS-CORSIM combines two of the most widely used traffic simulation models, NETSIM for surface streets and FRESIM for freeways. FRESIM is mainly for freeway system, and NETSIM is for roadways other than freeways.

Thus, in this project, NETSIM can be used to build up crossroads and parts of exit ramps, and FRESIM can be used to build up freeways and parts of exit ramps. Also, CORSIM can combine them into one network. Figure 3.2 shows a network example combining NETSIM and FRESIM in TSIS.

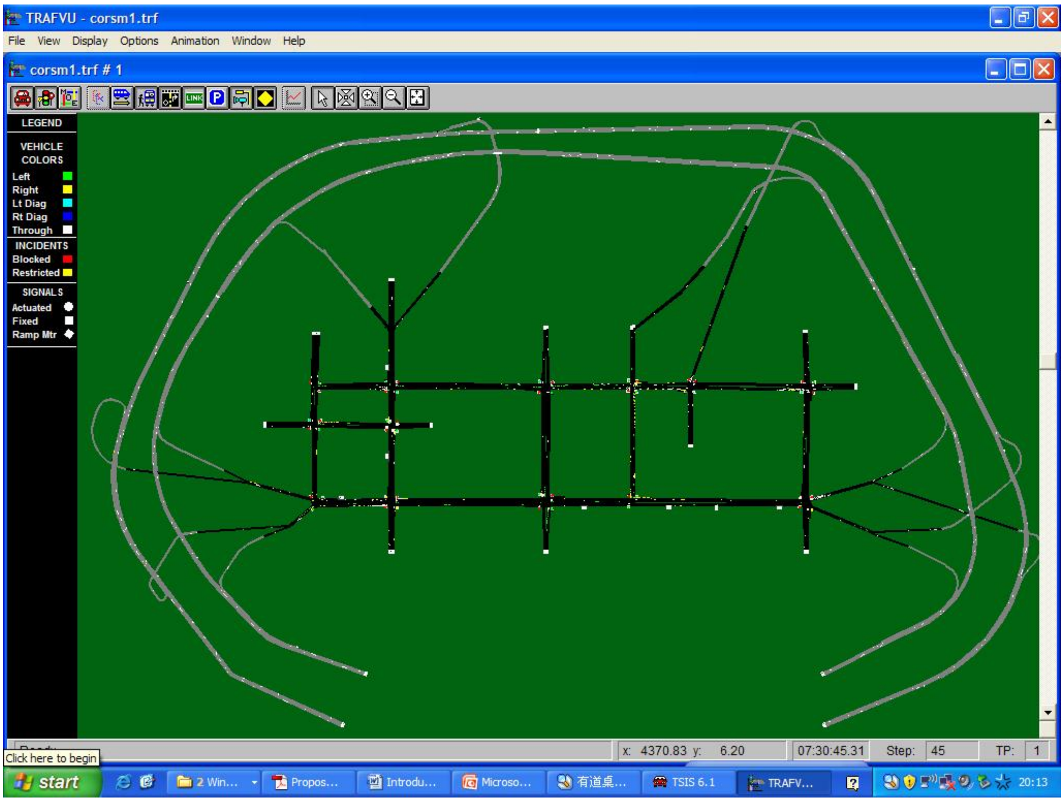

Figure 3.2 NETSIM and FRESIM in TSIS

In addition, TSIS-CORSIM also provides several demo projects for different subjects, which helps to understand the simulation process. These demo projects are as follows:

- Actuated Control Demo: This project demonstrates the operation of actuated control in the CORSIM model.
- CORSIM City Demo: This project demonstrates the capabilities of the TSIS package in creating and simulating a wide variety of different roadway configurations and interchanges.
- Incident Demo: This project demonstrates the effects of a freeway incident (accident) on a freeway and its surrounding arterials as modeled by CORSIM.

- EV Example: Emergency vehicles can cause signal pre-emption, follow specific routes, and travel at excess speeds.
- Interchange Demo: This project demonstrates the operation of the CORSIM surface-street interchange feature.
- Surface and Freeway Demo: This combined surface-street and freeway project demonstrates many features of the CORSIM model, including intersection controller and bus operations.
- Left Hand Examples: This project demonstrates left-hand drive within the CORSIM model, including intersection controller and roundabout operations.

3.2 Simulation Procedure

There are several typical steps for a complete TSIS simulation application:

- Step 1: Geometry data input. This step includes nodes, links, frameworks, property of node and link. Detailed factors are lane assignment, length, width, grade, curve, median, sign, mark, etc.
- Step 2: Traffic data input. This step mainly inputs traffic volume and related data, such as hourly volume, heavy vehicle, bicycle, pedestrian, bus, bus station, etc.; not only total volume needs to be input, but also volume for each turning direction should be indicated.
- Step 3: Traffic control data input. This step tells TSIS the type of traffic control. Normally, signalized control is used for intersections at ramp terminals, downstream intersections, or upstream intersections. Even some

intersections are actuating control; they are considered as pre-time control intersections. Timing and phasing data are observed during peak hours, which keeps them constant.

- Step 4: Simulation running. After all data are accomplished, TSIS will start running. During this step, all warnings and errors can be stated, which indicate necessary correction. Because traffic flow is random, all simulation files and models were running multiple times, and average outputs were considered the final results in order to eliminate randomness of traffic.
- Step 5: Data output: TSIS can produce a report of all Measures of Effectiveness (MOEs), tables, and charts. Useful data are selected for further analysis.
- Step 6: Calibration: Some MOEs will be selected for calibration, such as queuing length at the intersection approach. TSIS output data and field data are compared to make sure the errors are under control. This step assures accuracy of the simulation.
- Step 7: Modeling: After data calibration is passed, useful data are chosen for mathematical modeling, presenting relationships among variables.

3.3 Methods for Operational Analysis

The whole network of each observed site in TSIS was divided into three sections: freeway section, exit ramp section, and crossroad section. These sections were separated for further analysis. Different MOEs were presented to evaluate the performance for each section. And for whole system calibration and validation, different sections were combined.

3.3.1 Freeway Section

In the freeway section, the main task was to find out whether the impacts of different exit ramps are significantly different based on operational analysis. If the impacts are different, there is a need to select an optimal one under certain conditions.

Based on previous studies and data collection, number of lane changes, average speed, and delay time are considered the measures of effectiveness for operational performance evaluation.

(1) Number of Lane Changes

The number of lane changes is the total number of vehicles changing lanes in the freeway upstream section (1,500 ft before exit ramp) within one hour (see Figure 3.3).

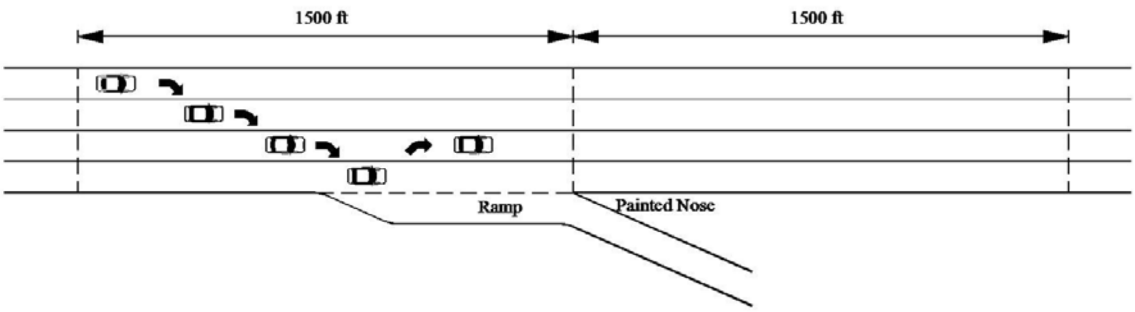

Figure 3.3 Number of lane changes

Number of lane changes is a significant factor that impacts operational performance on freeway sections adjacent to exit ramps. This change is mainly caused by exiting traffic to the ramp. The larger the number of lane changes, the worse the operational performance of the freeway. One kind of change is the exiting vehicles changing lanes from the left side thru lane to the right side ramp, which is called a mandatory lane change. The other kind of lane change happens between thru lanes just to find a better driving environment, which is an optional lane change. The last kind of number of lane change is the thru traffic changing lanes from the right side lane to the left.

Several independent variables may affect the number of lane changes, including ramp type, traffic volume, and number of thru lanes, etc. A mathematical model is presented to demonstrate the variable of number of lane changes.

$$Y = f(X_{12}, X_{13}, X_{14}, X_2, X_3, X_4, \ldots) \qquad \text{Eq. (1)}$$

Where,

Y —— number of lane change

X_{12} —— ramp type II

X_{13} —— ramp type III

X_{14} —— ramp type IV

X_2 —— freeway volume (vph)

X_3 —— exit rate (%)

X_4 —— number of thru lanes on freeway

(2) Average Speed

In addition to the number of lane changes, average speed on a freeway section is factor that can be used to estimate the impacts of the exit ramp. The larger of the average speed, the better the performance, and the less the probability of a crash.

The variables of ramp type, traffic volume, and number of thru lanes contribute to speed. A prediction model to estimate average speed is as follows:

$$Y = f(X_{12}, X_{13}, X_{14}, X_2, X_3, X_4, ...) \quad \text{Eq. (2)}$$

Where,

Y —— average speed

X_{12} —— ramp type II

X_{13} —— ramp type II

X_{14} —— ramp type IV

X_2 —— freeway volume (vph)

X_3 —— exit rate (%)

X_4 —— number of thru lanes on freeway

By using TSIS simulation, many scenarios are specified, such as the different levels of traffic, different thru lanes, and different ramp types. All the extended examples can help find the correlation ships.

(3) Delay Time

Delay time per vehicle on a freeway section indicates the impacts of the existence of the exit ramp. Ramp type is an important factor contributing to it. Field data show that exit ramp types can affect control delay on a freeway near a ramp area. A prediction model is presented to estimate control delay per vehicle, and the format is the same as model for number of lane changes and average speed.

$$Y = f(X_{12}, X_{13}, X_{14}, X_2, X_3, X_4, ...) \qquad \text{Eq. (3)}$$

Where,

Y —– delay time (s)

X_{12} —– ramp type II

X_{13} —– ramp type III

X_{14} —– ramp type IV

X_2 —– freeway volume (vph)

X_3 —– exit rate (%)

X_4 —– number of thru lanes on freeway

When different impacts of different ramp types are found under the same traffic and geometric conditions, there is evidence for choosing an optimal exit ramp for a certain situation. In addition to all three MOEs mentioned above, safety is another aspect for the selection. Results from the safety analysis also were used.

(4) Length Design for Deceleration Lane of Ramp Type I and IV

Besides number of lane change and speed standard deviation (S.D.), length design for the deceleration lane is another important issue. For ramp types I and IV, the length of the deceleration lane can be verified, and the change of length might impact the performance.

In simulation, the length is changed from 100 ft to 1500 ft in TSIS to see the distribution of MOE speed S.D. under a different level of volume. Actually, AASHTO's Green Book has already presented the proper length for freeway exit lanes, but the standards are mainly based on stop distance. New suggested distances are based on operational analysis.

3.3.2 Ramp Section

There are two issues related to the ramp section: determining the minimal length for a ramp and discussing the ramp configuration.

(1) Ramp Length Design

Ramp length design is based on the assumption that the minimum length of ramp must meet the requirements of holding exiting traffic, including queuing length, deceleration length, and perception-reaction distance. The exiting traffic spilling back onto the freeway must be avoided. The deceleration distance can be calculated by the initial speed and the deceleration rate, and the perception-reaction distance depends on speed and time. Queuing length needs simulation, which depends on geometry and traffic conditions together.

Several factors will affect the minimum ramp length, such as volume level, control type, number of lanes on ramp, ramp terminal, etc. Thus, all the independent variables will be changed to simulate respectively, in order to find the minimal queuing length under each scenario.

(2) Ramp configuration

The AASHTO Green Book listed three kinds of exit ramp configuration: type A, type B and type C, as shown in Figure 3.4.

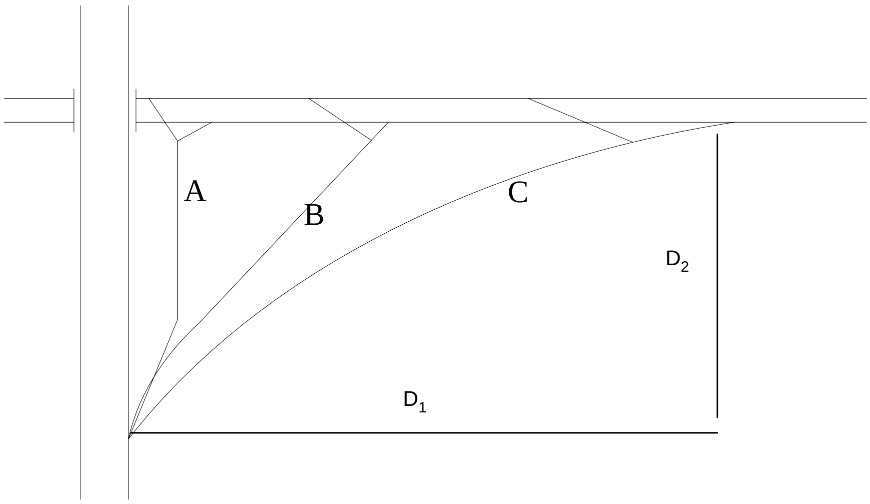

Figure 3.4 Exit ramp configurations

In a type A, the ramp terminal is close to the freeway, and the exit ramp is almost parallel to the freeway. This type is usually caused by limited land use. In type B, the ramp terminal is little farther away from the freeway and the length of the exit ramp is longer; the ramp is closer to straight, or the curve is sharp. In a type C, ramp the terminal is far enough from the freeway, and the ramp curve can be made smooth.

Two factors are changed that result in changes in operational performance, D_1 and D_2. (see Figure 3.4). Distance change is to find out how speed S.D. changes. A larger speed S.D. value under certain ramp configuration can cause potential problems.

3.3.3 Crossroad Section

The main task related to crossroads is to determine the minimal distance between the ramp terminal and the upstream/downstream intersection.

Take the distance between the ramp terminal and he downstream intersection as an example. Based on this assumption, it is calculated that the queuing length of vehicles on the crossroad does not block the traffic coming out from the exit ramp. For distance between the downstream intersection and the ramp terminal, the weaving distance is also considered in addition to queuing length. Figure 3.5 shows the general method for calculating minimum distance. There is not a specified minimal distance requirement between the ramp terminal and the upstream intersection, which is also the distance between two exit ramps at a diamond interchange. Several factors will impact this distance, such as geometric configuration and land use.

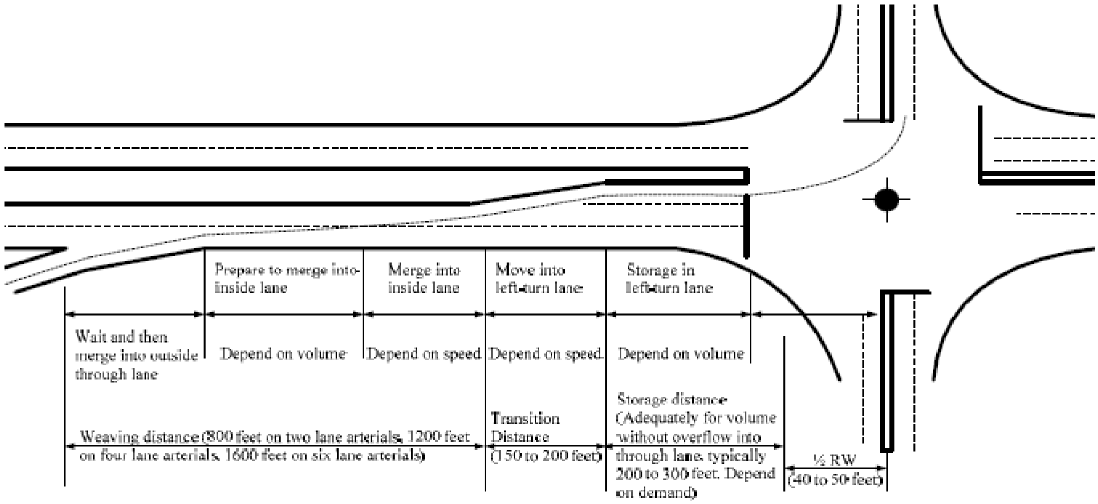

Figure 3.5 Distances between ramp terminal and downstream intersection

A minimal distance is presented here mainly based on queuing length simulation. This method assures that queuing length will not spill back from segments between the two exit ramps, which will worsen thru traffic conditions on the crossroad.

Figure 3.6 shows the simulation network in TSIS to test different distances when traffic volumes, signal timing plans, and the geometry conditions are changed. The minimum distance can be found under heavy traffic conditions.

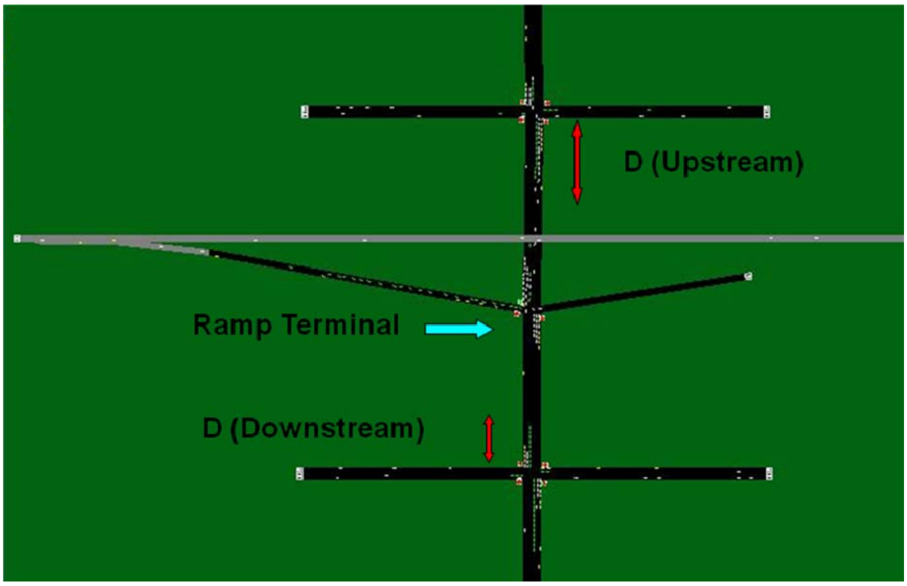

Figure 3.6 Distances between upstream/downstream intersection and ramp terminal

Chapter 4 Data Collection

This chapter mainly describes information about field data collection, including site selection, data collection equipment, data collection procedures, and data reduction. All collected field data were subject to simulation modeling and input requirements. The quality of data collection will impact the accuracy of the simulation results. Therefore, this part of the project was well prepared.

4.1 Site Selection

Site selection must be determined first. There were 13 sites selected for data collection in Florida. The selection criteria for all these sites were based on discussions among FDOT project officials and USF researchers, with the following requirements:

- All sites are freeway interchanges in central Florida.
- All sites are representative and typical in central Florida.
- All sites include the four different types of exit ramps.
- All sites serve a high traffic volume at peak hours.

Table 4.1 shows the locations and area of the 13 sites. All are located in the Tampa Bay and Orlando areas in central Florida. Figure 4.1 shows the exact scattergrams of the observed sites on a map of Florida. Generally, each completed interchange contains two exit ramps on the two opposite sides, and only two interchanges have one exit ramp. Thus, there are 24 exit ramps for the 13 sites. Table 4.2 shows the 24 exit ramps with detailed classifications of ramp types.

Table 4.1 Locations of 13 observed sites in Florida

No.	Location	Area
1	I-75 at SR 56	Tampa
2	I-4 at CR 579	Tampa
3	I-275 at Hillsborough Ave	Tampa
4	I-75 at I-4	Tampa
5	I-275 at Ulmerton Rd	St Petersburg
6	I-275 at 4th St	St Petersburg
7	I-75 at Fowler Ave	Tampa
8	I-4 at Universal Blvd	Orlando
9	I-4 at Conroy Rd	Orlando
10	I-4 at Lee Rd	Orlando
11	I-4 at Altamonte Dr	Orlando
12	I-4 at SR 434	Orlando
13	I-75 at CR 581 (Bruce B. Downs Blvd)	Tampa

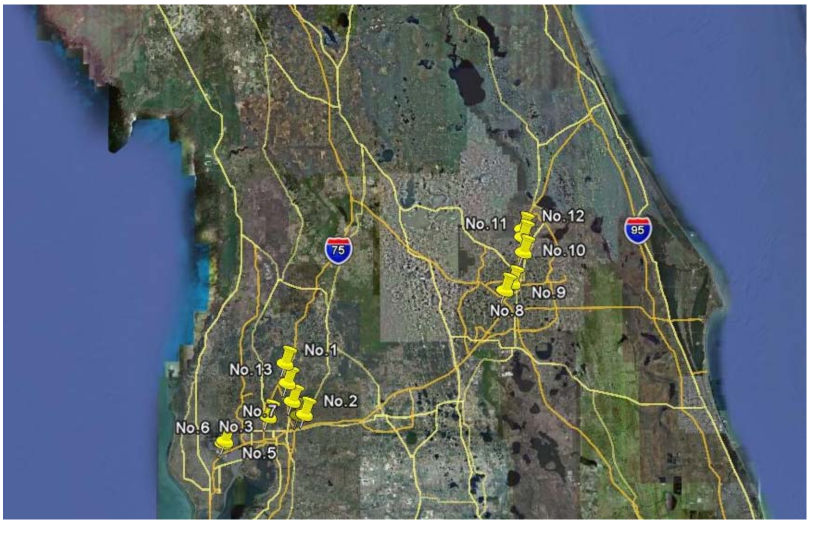

Figure 4.1 Scattergram of 13 observed sites in Florida

Table 4.2 Locations of 24 exit ramps with classification of ramp type

Ramp No.	Ramp Type	Ramp Location	Ramp Direction	Number of Thru Lanes on Freeway	Number of Lanes on Ramp
1	I	I-75 at SR 56	SB	2	1
2	I	I-4 at CR 579	WB	3	1
3	I	I-275 at Hillsborough Ave	NB	3	1
4	I	I-275 at Hillsborough Ave	SB	3	1
5	I	I-75 at I-4	SB	3	1
6	I	I-275 at 4th St	SB	4	1
7	I	I-4 at Universal Blvd	SB	3	1
8	I	I-75 at CR 581 (BBD)	SB	2	1
9	II	I-75 at Fowler Ave	SB	3	1
10	II	I-4 at Lee Rd	NB	4	1
11	II	I-4 at Lee Rd	SB	4	1
12	II	I-4 at SR 434	SB	4	1
13	III	I-75 at SR 56	NB	4	2
14	III	I-4 at CR 579	EB	4	2
15	III	I-4 at Universal Blvd	NB	4	2
16	III	I-4 at Conroy Rd	NB	5	2
17	III	I-4 at Conroy Rd	SB	5	2
18	III	I-4 at Altamonte Dr	NB	4	2
19	III	I-4 at SR 434	NB	4	2
20	III	I-4 at Altamonte Dr	SB	4	2
21	III	I-75 at CR 581 (BBD)	NB	3	2
22	IV	I-75 at I-4	NB	4	2
23	IV	I-275 at Ulmerton Rd	SB	4	2
24	IV	I-75 at Fowler Ave	NB	3	2

4.2 Data Collection Equipment

As many parameters were required, several pieces of equipment were used to assist with field data collection, including video cameras, traffic counters, radar guns, stop watches, traffic cones, etc. Detailed information (purpose and function) is shown as follows:

- Video Camera: to capture traffic volume and number of vehicles in a queue
- Traffic Counter: to assist video camera
- Radar Gun: to detect operating speed on roadway
- Stop Watch: to obtain timing plan for intersections
- Traffic Cones: to set a safety zone at roadside for all observers and equipment
- Rough Measurer: to measure geometry dimension
- Flash Coat: to protect observers by reminding other drivers

(a) Video camera with stand (b) Use of video camera in data collection

(c) Traffic counter (d) Use of traffic counter in data collection

Figure 4.2 Data collection equipment

(e) Radar gun

(f) Use of radar gun in data collection

(g) Stop watch

(h) Traffic cone

(i) Rough measurer

(j) Flash coat

Figure 4.2 (Continued)

4.3 Data Collection Procedures

Data collection was divided into three sections: freeway section, exit ramp section, and crossroad section. Several kinds of data were collected for these three sections, such as traffic volume, heavy vehicles (%), operation speed, signal timing plan, number of lane changes, number of lanes, turn lane assignment, etc. All the data were collected at peak hours in order to capture the high volume situation of operation. The peak hour times were to two hours for both the morning and afternoon peaks (7:00 – 9:00 AM, and 4:00 – 6:00 PM) because of the long time of observation. Based on some data already gained, the range of peak hour time is proper due to the relatively constant traffic.

For the freeway section, the hourly traffic volume of each lane was collected by video camera with the ratio of heavy vehicles, and the operation speed was collected by radar gun. The number of lane changes was also captured by video camera in the 1500 ft upstream section of the exit ramp.

For the ramp section, in addition to the hourly traffic volume of each lane, the timing plan for the ramp terminal and the queuing length for each lane at each approach was also captured.

For the crossroad section, data collection was mainly focused on the upstream and downstream intersections. All traffic data (volume, assignment, etc.) and timing data were collected, as most intersections were signalized. A radar gun was used to detect the operational speed of all approaches on the crossroad. Google Earth was used to collect geometric data, including number of lanes, turn bays at intersections, lane width, curvature, median, channelized island, etc. Table 4.3 and Figure 4.3 demonstrate the comprehensive method of data collection.

Table 4.3 Time period and method for all data collection

Observing Time	Parameters	Methods
7:00 to 8:00 AM or 5:00 to 6:00 PM	Hourly volume of each lane and total HV ratio in freeway	Counted by observer
	Number of lane changes on freeway in front of painted nose of exit ramp	Counted by observer
	Hourly volume of each lane and total HV ratio in ramp terminal	By video camera
	Queuing length of each lane in ramp terminal	By video camera
	Signal timing and phasing at ramp terminal	Read by observer using timer
	Speed on freeway and ramp	By radar gun
8:00 to 9:00 AM or 6:00 to 7:00 PM	Hourly volume of each lane and total HV ratio of each approach (downstream intersection)	By video camera
	Queuing length of each lane in each approach (downstream intersection)	By video camera
	Signal timing and phasing at downstream intersection	Read by observer using timer
	Hourly volume of each lane and total HV ratio of each approach (upstream intersection)	By video camera
	Queuing length of each lane in each approach (upstream intersection)	By video camera
	Signal timing and phasing at upstream intersection	Read by observer using timer
	Speed on downstream and upstream intersection	By radar gun

Some signalized intersections were actuating control, whose timing plan were affected by traffic volume and might vary at each cycle. It is difficult to get the actuating timing plan from observation, because it depends on values such as minimal initial time, minimal crossing time, etc., which are difficult to know. A decision was made to simplify the observation and get a reasonable result by setting pre-timed signalized control for these intersections by using the average timing plan from actuating signal. This method had been attested to through field data. The split time for each phase was pretty close because of the relevantly constant traffic at the peak hours.

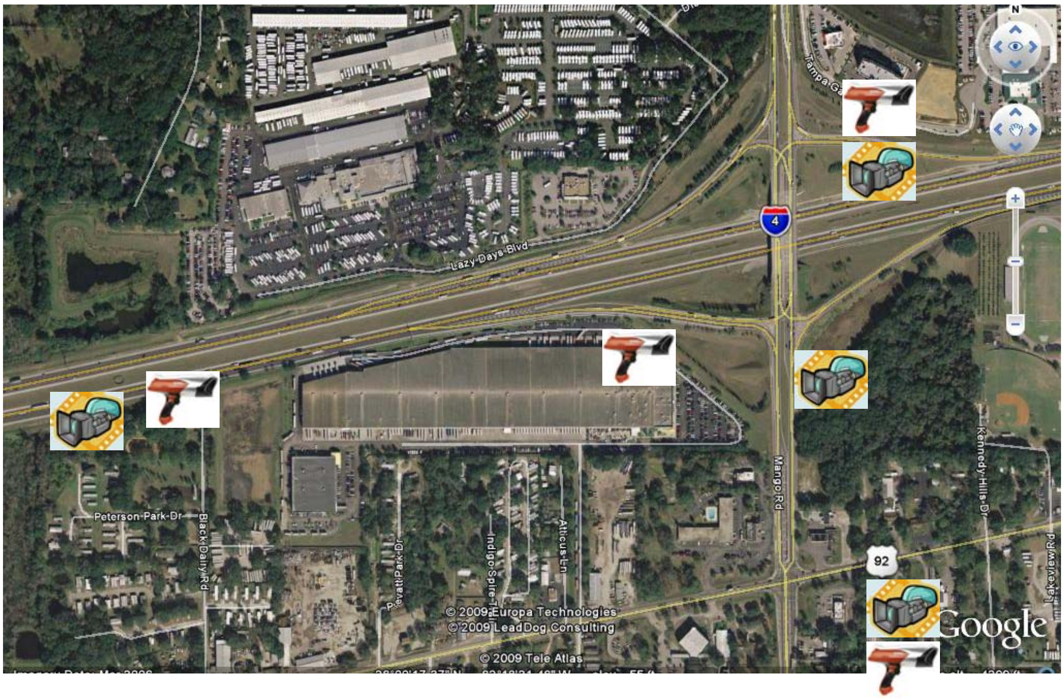

Figure 4.3 Location of devices for data collection

4.4 Data Reduction

After data collection was completed, data reduction was conducted. All video camera data were read and transferred to a computer, timing data were calculated, and data recorded on paper were input into electronic file. Because not all field data were collected at the same time, it is reasonable that some data do not match. If this happened, error was controlled to less than 5%, or data collection was conducted again until it was less than 5%.

Final field data for each observed site are shown in Tables 4-4 through 4-25, which includes two directions (NB and SB, or EB and WB).

Table 4.4 I-4 at Conroy Road (NB)

Freeway				
Basic number of lanes	4		Volume of ramp	1038
Volume of each lane (from left to right)	1137, 1296, 954, 486		Exit ramp type	III
Number of lanes on ramp	2		Number of lane changes on freeway	72
Ramp Terminal				
Traffic Volume				
EB: 1083	WB: 801		SB: 0	NB: 1038
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB	16	3	1
2	EB and WB	36	3	1
Downstream Intersection				
Traffic Volume				
EB: 393	WB: 498		SB: 978	NB: 708
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	14	3	1
2	EB and WB thru	14	3	1
3	SB	26	3	1
4	SB and NB thru	24	3	1
5	NB	44	3	1
Upstream Intersection				
Traffic Volume				
EB: 974	WB: 1043		SB: 603	NB: 845
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	10	3	1
2	EB and WB thru	12	3	1
3	SB	15	3	1
4	SB and NB thru	26	3	1
5	NB	26	3	1

Table 4.5 I-4 at Conroy Road (SB)

Freeway				
Basic number of lanes	5	Volume of ramp	1052	
Volume of each lane (from left to right)	1892,1594,1078, 696,740	Exit ramp type	III	
Number of lanes on ramp	2	Number of lane changes on freeway	216	
Ramp Terminal				
Traffic Volume				
EB: 2118	WB: 2367	SB: 1052	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB	12	3	1
2	EB and WB thru	40	3	1
Downstream Intersection				
Traffic Volume				
EB: 1083	WB: 1287	SB: 705	NB: 1116	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	11	3	1
2	EB and WB thru	16	3	1
3	SB	17	3	1
4	SB and NB thru	34	3	1
5	NB	20	3	1
Upstream Intersection				
Traffic Volume				
EB: 1947	WB: 1578	SB: 0	NB: 1874	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB	34	3	1
2	EB left and thru	31	3	1
3	EB and WB thru	42	3	1

Table 4.6 I-4 at Altamonte Drive (SB)

Freeway				
Basic number of lanes	3	Volume of ramp	645	
Volume of each lane (from left to right)	1284,1338,1257	Exit ramp type	III	
Number of lanes on ramp	2	Number of lane changes on freeway	36	
Ramp Terminal				
Traffic Volume				
EB: 1629	WB: 2271	SB: 396	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB	35	3	1
2	WB thru and left	36	3	1
3	EB and WB thru	60	3	1
Downstream Intersection				
Traffic Volume				
EB: 1578	WB: 1908	SB: 441	NB: 528	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	WB	17	3	1
2	EB and WB thru	36	3	1
3	EB	19	3	1
4	SB and NB left	17	3	1
5	SB and NB thru	21	3	1
Upstream Intersection				
Traffic Volume				
EB: 1776	WB: 1668	SB: 0	NB: 1008	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB	32	3	1
2	EB and WB thru	71	3	1
3	EB thru and left	28	3	1

Table 4.7 I-4 at Altamonte Drive (NB)

Freeway				
Basic number of lanes	3	Volume of ramp	1098	
Volume of each lane (from left to right)	1710,1716,882	Exit ramp type	III	
Number of lanes on ramp	2	Number of lane changes on freeway	78	
Ramp Terminal				
Traffic Volume				
EB: 2655	WB: 3669	SB: 0	NB: 1728	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB	42	3	1
2	EB and WB thru	76	3	1
3	EB thru and left	33	3	1
Downstream Intersection				
Traffic Volume				
EB: 2258	WB: 1923	SB: 372	NB: 477	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB thru and left	27	3	1
2	WB thru and left	43	3	1
3	EB and WB left	20	3	1
4	SB	20	3	1
5	NB	20	3	1
Upstream Intersection				
Traffic Volume				
EB: 1878	WB: 2133	SB: 714	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB	24	3	1
2	WB thru and left	34	3	1
3	EB and WB thru	81	3	1

Table 4.8 I-275 at 4th Street (SB)

Freeway			
Basic number of lanes	4	Volume of ramp	332
Volume of each lane (from left to right)	837,868,1185,965	Exit ramp type	II
Number of lanes on ramp	1	Number of lane changes on freeway	126
Ramp Terminal			
Traffic Volume			
EB: 47	WB: 43	SB: 298	NB: 552
Timing and Phasing (This intersection is yield controlled, SB and NB approaches belong to main road, and EB and WB approaches belong to minor road.)			
Downstream Intersection			
Traffic Volume			
EB: 38	WB: 27	SB: 261	NB: 487
Timing and Phasing (This intersection is yield controlled, SB and NB approaches belong to main road, and EB and WB approaches belong to minor road.)			

Table 4.9 I-75 at SR 56 (SB)

Freeway				
Basic number of lanes	2	Volume of ramp	731	
Volume of each lane (from left to right)	873,767	Exit ramp type	II	
Number of lanes on ramp	1	Number of lane changes on freeway	38	
Ramp Terminal				
Traffic Volume				
EB: 674	WB: 1097	SB: 719	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB	24	3	1
2	WB left	16	3	1
3	EB and WB thru	30	3	1
Downstream Intersection				
Traffic Volume				
EB: 1095	WB: 993	SB: 734	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	29	3	1
2	EB left	17	3	1
3	EB and WB thru	31	3	1
Upstream Intersection				
Traffic Volume				
EB: 737	WB: 972	SB: 0	NB: 530	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB	21	3	1
2	EB left	17	3	1
3	EB and WB thru	27	3	1

Table 4.10 I-75 at SR 56 (NB)

<table>
<tr><td colspan="5">Freeway</td></tr>
<tr><td>Basic number of lanes</td><td>4</td><td colspan="2">Volume of ramp</td><td>1056</td></tr>
<tr><td>Volume of each lane (from left to right)</td><td>1001,876,831,1113</td><td colspan="2">Exit ramp type</td><td>III</td></tr>
<tr><td>Number of lanes on ramp</td><td>2</td><td colspan="2">Number of lane changes on freeway</td><td>103</td></tr>
<tr><td colspan="5">Ramp Terminal</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 978</td><td>WB: 1421</td><td>SB: 0</td><td colspan="2">NB: 996</td></tr>
<tr><td colspan="5">Timing and Phasing</td></tr>
<tr><td>Phase</td><td>Maneuver</td><td>Green (s)</td><td>Yellow (s)</td><td>All Red (s)</td></tr>
<tr><td>1</td><td>NB</td><td>26</td><td>3</td><td>1</td></tr>
<tr><td>2</td><td>EB left</td><td>15</td><td>3</td><td>1</td></tr>
<tr><td>3</td><td>EB and WB thru</td><td>39</td><td>3</td><td>1</td></tr>
<tr><td colspan="5">Downstream Intersection</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 871</td><td>WB: 1341</td><td>SB: 16</td><td colspan="2">NB: 23</td></tr>
<tr><td colspan="5">Timing and Phasing
(This intersection is yield controlled, EB and WB approaches belong to main road, and SB and NB approaches belong to minor road.)</td></tr>
<tr><td colspan="5">Upstream Intersection</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 1021</td><td>WB: 1209</td><td>SB: 767</td><td colspan="2">NB: 0</td></tr>
<tr><td colspan="5">Timing and Phasing</td></tr>
<tr><td>Phase</td><td>Maneuver</td><td>Green (s)</td><td>Yellow (s)</td><td>All Red (s)</td></tr>
<tr><td>1</td><td>SB</td><td>24</td><td>3</td><td>1</td></tr>
<tr><td>2</td><td>WB left</td><td>21</td><td>3</td><td>1</td></tr>
<tr><td>3</td><td>EB and WB thru</td><td>36</td><td>3</td><td>1</td></tr>
</table>

Table 4.11 I-4 at CR 579 (WB)

Freeway				
Basic number of lanes	3	Volume of Ramp	983	
Volume of each lane (from left to right)	330,687,240	Exit ramp type	II	
Number of lanes on ramp	1	Number of lane changes on freeway	46	
Ramp Terminal				
Traffic Volume				
EB: 0	WB: 945	SB: 1250	NB: 1876	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	WB	20	3	1
2	NB and SB thru	33	3	1
3	NB thru and left	18	3	1
Downstream Intersection				
Traffic Volume				
EB: 331	WB: 64	SB: 1654	NB: 634	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB and SB left	12	3	1
2	NB and SB thru	24	3	1
3	EB and WB	16	3	1
Upstream Intersection				
Traffic Volume				
EB: 1184	WB: 0	SB: 1342	NB: 1653	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB	23	3	1
2	NB and SB thru	38	3	1
3	NB thru and left	14	3	1

Table 4.12 I-4 at CR 579 (EB)

Freeway				
Basic number of lanes	4	Volume of Ramp	1140	
Volume of each lane (from left to right)	870,934,656,1240	Exit ramp type	III	
Number of lanes on ramp	2	Number of lane changes on freeway	87	
Ramp Terminal				
Traffic Volume				
EB: 1089	WB: 0	SB: 1243	NB: 1709	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB	28	3	1
2	NB and SB thru	42	3	1
3	NB thru and left	21	3	1
Downstream Intersection				
Traffic Volume				
EB: 351	WB: 478	SB: 1457	NB: 960	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB	26	3	1
2	NB and SB left	19	3	1
3	NB and SB thru	37	3	1
Upstream Intersection				
Traffic Volume				
EB: 0	WB: 670	SB: 813	NB: 1534	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	WB	23	3	1
2	NB and SB thru	35	3	1
3	NB thru and left	27	3	1

Table 4.13 I-275 at Ulmerton Road (SB)

Freeway			
Basic number of lanes	3	Volume of each ramp	1784
Volume of each lane (from left to right)	654,886,704	Exit ramp type	II
Number of lanes on ramp	2	Number of lane changes on freeway	57
Ramp Terminal[1]			
Traffic Volume			
EB: 1194	WB: 1542	SB: 0	NB: 15
Timing and Phasing (This intersection is yield controlled; EB and WB approaches belong to main road, and NB approach belongs to minor road.)			
Downstream Intersection[1]			
Traffic Volume			
EB: 1023	WB: 1439	SB: 16	NB: 23
Timing and Phasing (This intersection is yield controlled, EB and WB approaches belong to main road, and SB and NB approaches belong to minor road.)			
Ramp Terminal[2]			
Traffic Volume			
EB: 354	WB: 0	SB: 363	NB: 225
Timing and Phasing (This intersection is yield controlled, NB and SB approaches belong to main road, and EB approach belongs to minor road.)			
Downstream Intersection[2]			
Traffic Volume			
EB: 379	WB: 0	SB: 371	NB: 209
Timing and Phasing (This intersection is yield controlled, NB and SB approaches belong to main road, and EB approach belongs to minor road.)			

Table 4.14 I-4 at SR 434 (SB)

Freeway				
Basic number of lanes	3	Volume of ramp	1103	
Volume of each lane (from left to right)	1764, 1572, 769	Exit ramp type	I	
Number of lanes on ramp	1	Number of lane changes on freeway	76	
Ramp Terminal				
Traffic Volume				
EB: 1789	WB: 1702	SB: 1021	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	28	3	1
2	WB thru & left	46	3	1
3	EB and WB thru	147	3	1
Downstream Intersection				
Traffic Volume				
EB: 1346	WB: 1156	SB: 346	NB: 451	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB thru	24	3	1
2	EB thru & left	42	3	1
3	WB thru & left	19	3	1
4	SB and NB left	39	3	1
5	SB and NB thru	21	3	1
Upstream Intersection				
Traffic Volume				
EB: 1453	WB: 1134	SB: 0	NB: 987	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB left	22	3	1
2	EB and WB thru	46	3	1
3	NB left	19	3	1
4	EB and WB left	37	3	1

Table 4.15 I-4 at SR 434 (NB)

Freeway				
Basic number of lanes	3	Volume of ramp	1011	
Volume of each lane (from left to right)	2184, 1752, 735	Exit ramp type	III	
Number of lanes on ramp	2	Number of lane changes on freeway	96	
Ramp Terminal				
Traffic Volume				
EB: 1944	WB: 1647	SB: 0	NB: 1164	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB left	24	3	1
2	EB and WB thru	50	3	1
3	NB left	21	3	1
4	EB and WB left	41	3	1
Downstream Intersection				
Traffic Volume				
EB: 1767	WB: 1575	SB: 198	NB: 798	
Timing and Phasing				
1	SB left	24	3	1
2	WB thru & left	47	3	1
3	SB left	22	3	1
4	EB and WB thru	146	3	1
Upstream Intersection				
Traffic Volume				
EB: 1797	WB: 1692	SB: 879	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB thru	85	3	1
2	NB thru & left	32	3	1
3	EB and WB left	17	3	1
4	SB thru & left	17	3	1
5	EB thru & left	15	3	1

Table 4.16 I-75 at Fowler Avenue (SB)

Freeway				
Basic number of lanes	2	Volume of Ramp	1057	
Volume of each lane (from left to right)	1765, 1457	Exit ramp type	IV	
Number of lanes on ramp	2	Number of lane changes on freeway	87	
Ramp Terminal				
Traffic Volume				
EB: 1579	WB: 1764	SB: 667	NB: 0	
Timing and Phasing				
Ramp terminal is yield control.				
Downstream Intersection				
Traffic Volume				
EB: 1701	WB: 1879	SB: 430	NB: 391	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	29	3	1
2	EB and WB thru	120	3	1
3	NB and SB left	20	3	1
4	NB and SB thru	33	3	1
Upstream Intersection				
Traffic Volume				
EB: 1684	WB: 1760	SB: 0	NB: 572	
Timing and Phasing				
Upstream intersection is yield control.				

Table 4.17 I-75 at Fowler Avenue (NB)

Freeway			
Basic number of lanes	2	Volume of Ramp	998
Volume of each lane (from left to right)	1543, 1321	Exit ramp type	IV
Number of lanes on ramp	2	Number of lane changes on freeway	75
Ramp Terminal			
Traffic Volume			
EB: 1589	WB: 1549	SB: 0	NB: 754
Timing and Phasing			
Ramp terminal is yield control.			
Downstream Intersection			
Traffic Volume			
EB: 1356	WB: 1305	SB: 75	NB: 0
Timing and Phasing			
Downstream intersection is yield control.			
Upstream Intersection			
Traffic Volume			
EB: 1621	WB: 1678	SB: 574	NB: 0
Timing and Phasing			
Upstream intersection is yield control.			

Table 4.18 I-4 at I-75 (SB)

Freeway			
Basic number of lanes	2	Volume of ramp	773
Volume of each lane (from left to right)	1543, 1059	Exit ramp type	I
Number of lanes on ramp	1	Number of lane changes on freeway	56
Ramp Terminal			
Traffic Volume			
EB: 1734	WB: 1521	SB: 773	NB: 0
Timing and Phasing			
Ramp terminal is yield control.			
Downstream Intersection			
Traffic Volume			
EB: 1712	WB: 1671	SB: 346	NB: 0
Timing and Phasing			
Downstream intersection is yield control.			
Upstream Intersection			
Traffic Volume			
EB: 1653	WB: 1534	SB: 0	NB: 549
Timing and Phasing			
Upstream intersection is yield control.			

Table 4.19 I-4 at I-75 (NB)

Freeway			
Basic number of lanes	3	Volume of ramp	1214
Volume of each lane (from left to right)	1987, 1552, 741	Exit ramp type	IV
Number of lanes on ramp	2	Number of lane changes on freeway	121
Ramp Terminal			
Traffic Volume			
EB: 1744	WB: 1529	SB: 0	NB: 621
Timing and Phasing			
Ramp terminal is yield control.			
Downstream Intersection			
Downstream intersection is another ramp of freeway, not the cross street. Furthermore, the distance is about 4750 feet, which exceeds ramp influence distance of 1500 feet. Therefore, ignore existence of downstream intersection.			
Upstream Intersection			
Traffic Volume			
EB: 1697	WB: 1492	SB: 679	NB: 0
Timing and Phasing			
Upstream intersection is yield control.			

Table 4.20 I-275 at Hillsborough Avenue (SB)

Freeway				
Basic number of lanes	4	Volume of Ramp	831	
Volume of each lane (from left to right)	1721, 1636, 1201, 698	Exit ramp type	II	
Number of lanes on ramp	1	Number of lane changes on freeway	97	
Ramp Terminal				
Traffic Volume				
EB: 1235	WB: 1198	SB: 827	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	22	3	1
2	WB thru & left	16	3	1
3	EB and WB thru	32	3	1
Downstream Intersection				
Traffic Volume				
EB: 1301	WB: 1279	SB: 730	NB: 491	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	17	3	1
2	EB and WB thru	49	3	1
3	NB and SB left	13	3	1
4	NB and SB thru	16	3	1
Upstream Intersection				
Traffic Volume				
EB: 1284	WB: 1260	SB: 0	NB: 452	
Timing and Phasing				
Upstream intersection is yield control.				

Table 4.21 I-275 at Hillsborough Avenue (NB)

Freeway				
Basic number of lanes	3		Volume of Ramp	547
Volume of each lane (from left to right)	1641, 1410, 882		Exit ramp type	II
Number of lanes on ramp	1		Number of lane changes on freeway	54
Ramp Terminal				
Traffic Volume				
EB: 1389	WB: 1349		SB: 0	NB: 554
Timing and Phasing				
Ramp terminal is yield controlled.				
Downstream Intersection				
Traffic Volume				
EB: 1456	WB: 1405		SB: 75	NB: 0
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	EB and WB left	21	3	1
2	EB and WB thru	65	3	1
3	SB and NB left	19	3	1
4	SB and NB thru	26	3	1
Upstream Intersection				
Traffic Volume				
EB: 1221	WB: 1378		SB: 674	NB: 0
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	23	3	1
2	WB thru & left	17	3	1
3	EB and WB thru	41	3	1

Table 4.22 I-4 at Universal Blvd. (NB)

<table>
<tr><td colspan="5">Freeway</td></tr>
<tr><td>Basic number of lanes</td><td>4</td><td colspan="2">Volume of Ramp</td><td>164 (HV 4%),
340 (HV 4%)</td></tr>
<tr><td>Volume of each lane (from left to right)</td><td>1644 (HV 2%), 1584 (HV 3%), 1196 (HV 3%), 252 (HV 4%)</td><td colspan="2">Exit ramp type</td><td>III</td></tr>
<tr><td>Number of lanes on ramp</td><td>2</td><td colspan="2">Number of lane changes on freeway</td><td>164</td></tr>
<tr><td colspan="5">Ramp Terminal</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 1296</td><td>WB: 0</td><td colspan="2">SB: 776</td><td>NB: 694</td></tr>
<tr><td colspan="5">Timing and Phasing</td></tr>
<tr><td>Phase</td><td>Maneuver</td><td>Green (s)</td><td>Yellow (s)</td><td>All Red (s)</td></tr>
<tr><td>1</td><td>EB left and right</td><td>39</td><td>3</td><td>1</td></tr>
<tr><td>2</td><td>SB thru and left</td><td>30</td><td>3</td><td>1</td></tr>
<tr><td>3</td><td>NB thru and right</td><td>29</td><td>3</td><td>1</td></tr>
<tr><td colspan="5">Downstream Intersection</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 996</td><td>WB: 1080</td><td colspan="2">SB: 780</td><td>NB: 642</td></tr>
<tr><td colspan="5">Timing and Phasing</td></tr>
<tr><td>Phase</td><td>Maneuver</td><td>Green (s)</td><td>Yellow (s)</td><td>All Red (s)</td></tr>
<tr><td>1</td><td>EB & WB left</td><td>15</td><td>3</td><td>1</td></tr>
<tr><td>2</td><td>EB thru and left</td><td>24</td><td>3</td><td>1</td></tr>
<tr><td>3</td><td>EB & WB thru</td><td>47</td><td>3</td><td>1</td></tr>
<tr><td>4</td><td>NB & SB left</td><td>13</td><td>3</td><td>1</td></tr>
<tr><td>5</td><td>NB & SB thru</td><td>27</td><td>3</td><td>1</td></tr>
<tr><td colspan="5">Upstream Intersection</td></tr>
<tr><td colspan="5">Traffic Volume</td></tr>
<tr><td>EB: 1296</td><td>WB: 0</td><td colspan="2">SB: 1476</td><td>NB: 834</td></tr>
<tr><td colspan="5">Timing and Phasing</td></tr>
<tr><td>Phase</td><td>Maneuver</td><td>Green (s)</td><td>Yellow (s)</td><td>All Red (s)</td></tr>
<tr><td>1</td><td>EB</td><td>22</td><td>3</td><td>1</td></tr>
<tr><td>2</td><td>NB & SB left</td><td>19</td><td>3</td><td>1</td></tr>
<tr><td>3</td><td>NB & SB through</td><td>42</td><td>3</td><td>1</td></tr>
</table>

Table 4.23 I-4 at Universal Blvd. (SB)

Freeway				
Basic number of lanes	3	Volume of Ramp	564 (HV 0%)	
Volume of each lane (from left to right)	1398 (HV 2%), 1404 (HV 3%), 1089 (HV 3%)	Exit ramp type	II	
Number of lanes on ramp	1	Number of lane changes on freeway	108	
Ramp Terminal				
Traffic Volume				
EB: 498	WB: 765	SB: 0	NB: 396	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB left and right	20	3	1
2	WB thru and left	16	3	1
3	EB & WB thru	22	3	1
Downstream Intersection				
Traffic Volume				
EB: 0	WB: 741	SB: 1050	NB: 27	
Timing and Phasing				
It is yield controlled. EB and WB are the major approaches, and NB is the minor approach.				
Upstream Intersection				
Traffic Volume				
EB: 648	WB: 0	SB: 738	NB: 888	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	WB thru & left	39	3	1
2	NB & SB left	6	3	1
3	SB thru & left	21	3	1
4	NB & SB thu	75	3	1

Table 4.24 I-4 at Lee Road (SB)

Freeway				
Basic number of lanes	4		Volume of Ramp	894 (HV 0%)
Volume of each lane (from left to right)	2262 (HV 0%), 1929 (HV 1%), 1626 (HV 0.5%), 966 (HV 0%)		Exit ramp type	II
Number of lanes on ramp	1		Number of lane changes on freeway	54
Ramp Terminal				
Traffic Volume				
EB: 1131	WB: 909		SB: 894	NB: 0
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	33	3	1
2	EB & WB thru	62	3	1
3	WB thru and left	35	3	1
Downstream Intersection				
Traffic Volume				
EB: 1128	WB: 1357		SB: 311	NB: 0
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB thru & left	16	3	1
2	WB thru and left	5	3	1
3	EB & WB thru	90	3	1
4	EB thru & left	15	3	1
Upstream Intersection				
Traffic Volume				
EB: 1485	WB: 1461		SB: 0	NB: 618
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB left	36	3	1
2	EB thru & left	51	3	1
3	EB & WB thru	41	3	1

Table 4.25 I-4 at Lee Road (NB)

Freeway				
Basic number of lanes	4		Volume of Ramp	718 (HV 1%)
Volume of each lane (from left to right)	1712 (HV 1%), 1612 (HV 1%), 1872 (HV 1%), 718 (HV 1%)		Exit ramp type	II
Number of lanes on ramp	1		Number of lane changes on freeway	214
Ramp Terminal				
Traffic Volume				
EB: 2000	WB: 1480	SB: 0	NB: 652	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	NB left and right	15	3	1
2	EB thru and left	68	3	1
3	EB & WB thru	45	3	1
Downstream Intersection				
Traffic Volume				
EB: 1282	WB: 976	SB: 344	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB & NB left	8	3	1
2	SB & NB thru	13	3	1
3	EB thru & left	31	3	1
4	EB & WB thru	58	3	1
5	WB thru & left	13	3	1
Upstream Intersection				
Traffic Volume				
EB: 958	WB: 1024	SB: 494	NB: 0	
Timing and Phasing				
Phase	Maneuver	Green (s)	Yellow (s)	All Red (s)
1	SB left	32	3	1
2	EB & WB thru	62	3	1
3	WB thru & left	36	3	1

Chapter 5 Data Analysis and Results

Field data collection provided limited data for the simulation software. Simulation models changed several parameters randomly, such as traffic volume, geometry configuration, posted speed, signal timing, etc. Such changes extended the simulation samples from the initial 24 to thousands of sites. Therefore, this is a very efficient and reliable method for producing a great amount of data that can develop statistical models.

All results produced by CORSIM were from multi-runs (10 times). Parameters were changed within a reasonable range to enlarge the sample size. Parameter of travel time was selected for output validation (freeway section), error is controlled by 10%. Parameter of Queuing length was selected for output validation (ramp and cross road section), error is controlled by 15%. Some coefficients of driving behavior were adjusted for output validation. Table 5.1 shows how some variables were changed, table 5.2 shows how CORSIM global parameters were adjusted, and table 5.3 shows the final calibration and validation results.

Table 5.1 Change of selected variables

Parameters	Range
Ramp Type	I, II, III, IV
Freeway Volume (vphpl)	100 to 2000 (100 as increment)
Volume Exit Rate (%)	5% to 30% (5% as increment)
No. of Through Lane on Freeway	2, 3, 4

Table 5.2 Calibrated global parameters

Driver Type	1	2	3	4	5	6	7	8	9	10
Driver Type Percentage (%)	17	12	12	11	10	10	9	7	7	5
Acceptable Deceleration (fpss)	21	18	15	12	9	7	6	5	4	4
Acceptable Gap – Cross (s)	5.6	5.0	4.6	4.2	3.9	3.7	3.4	3.0	2.6	2.0
Acceptable Gap – Left (s)	7.8	6.6	6.0	5.4	4.8	4.5	4.2	3.9	3.6	2.7
Acceptable Gap – Right (s)	10.0	8.8	8.0	7.2	6.4	6.0	5.6	5.2	4.8	3.6

Table 5.3 Calibration and validation results

Section	Parameter	Error before C. & V.	Error after C. & V.
Freeway	Average Travel Time (s)	11.2% > 10%	8.9%
Ramp & Cross Road	Queuing Length (number of vehicle)	16.8% > 15%	14.6%

After all data were prepared, statistical models, such as linear and non-linear regression, were applied to develop forecast models for operational evaluations. All results are classified into three sections: freeway section, exit ramp section, and crossroad section.

5.1 Freeway Section

5.1.1 Number of Lane Changes

Comparisons of the number of lane changes among the four exit ramp types are shown from Figures 5.1 to Figure 5.3. In Figure 5.1, the freeway volume is 3600 vph, the number of thru lanes on the freeway is 3, and the number of lane changes increases with the ramp volume increasing. In Figure 5.2, the ramp volume is 800 vph, the number of thru lanes on the freeway is 3, and the number of lane changes increases lightly with the freeway volume increasing. In Figure 5.3, the freeway volume is 3600 vph, the ramp volume is 800 vph, and the number of lane changes increases with number of thru lanes increasing. Thus, all the three independent variables have positive impacts on the number of lane changes. Under the same conditions, exit ramp type IV has the largest number of lane changes, and type I has the smallest number of lane changes.

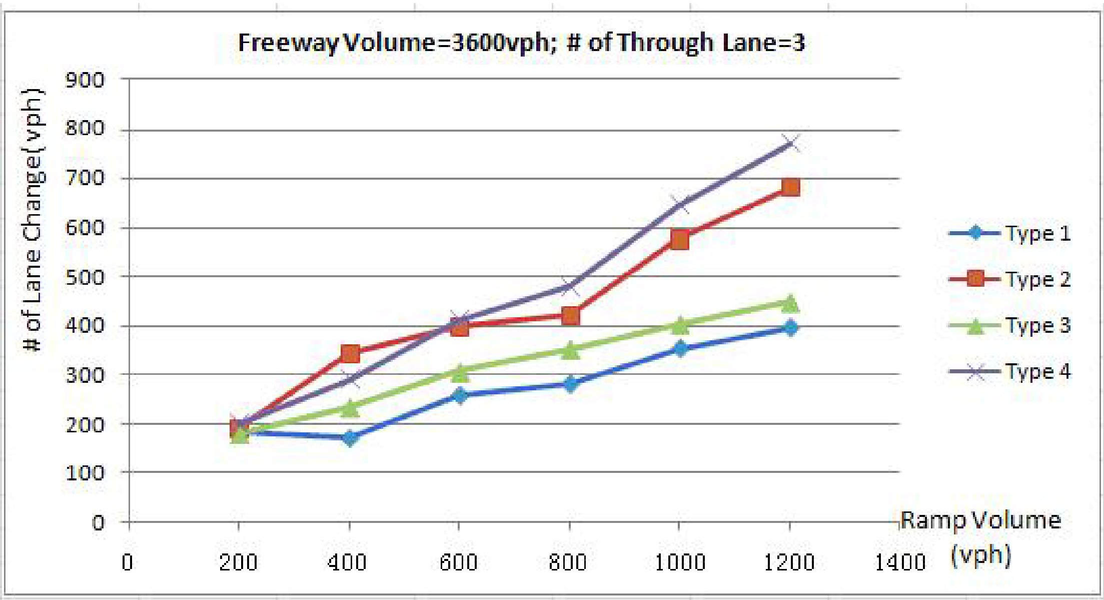

Figure 5.1 Number of lane changes vs. ramp volume

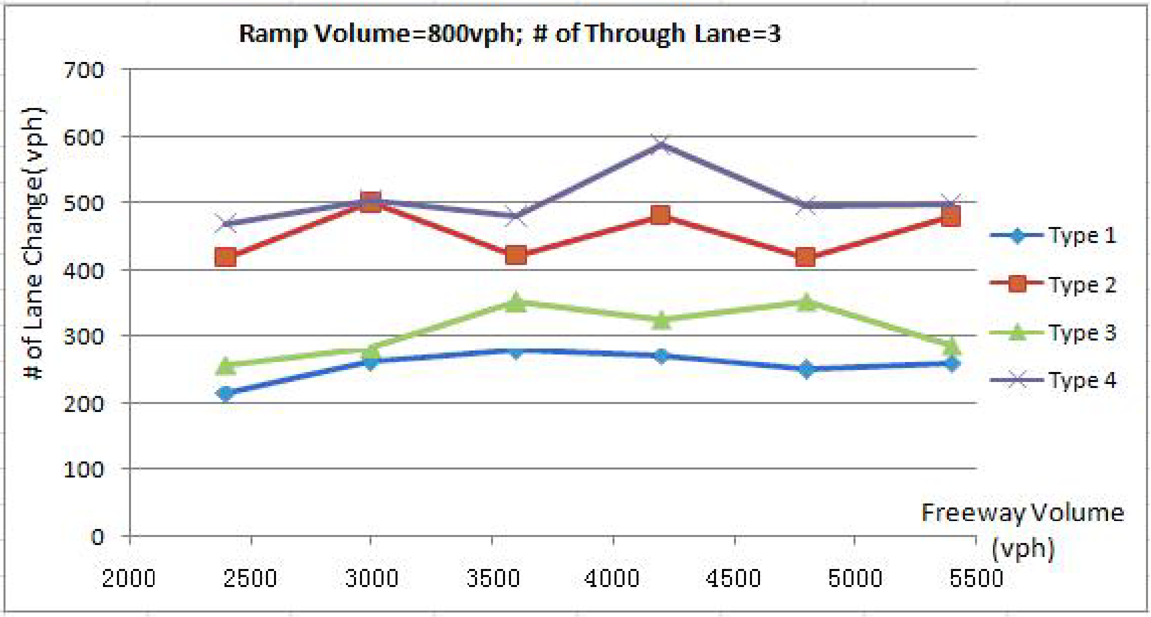

Figure 5.2 Number of lane changes vs. freeway volume

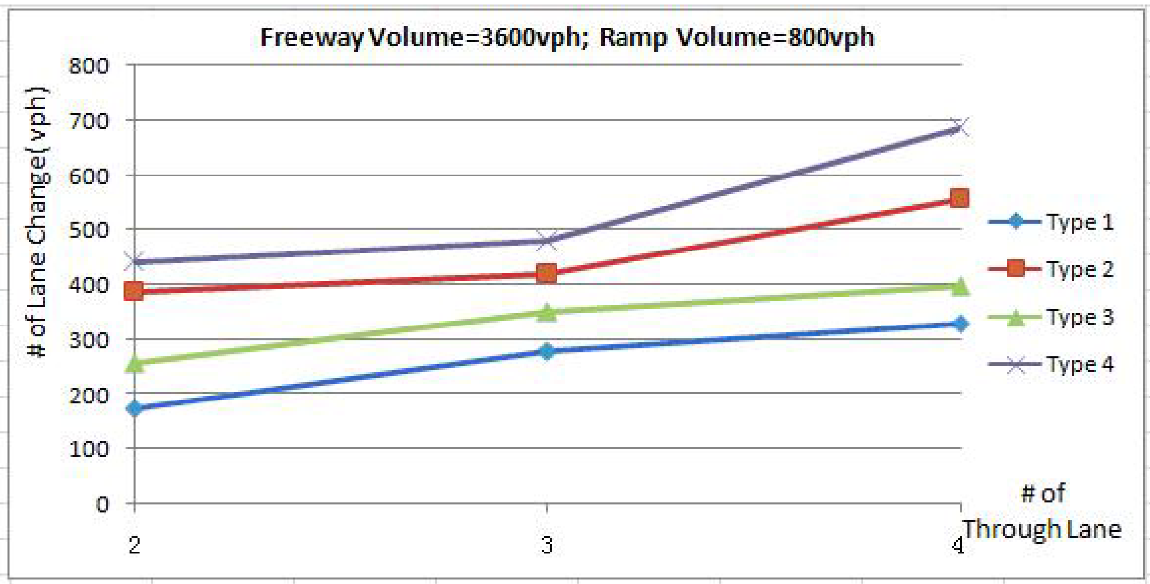

Figure 5.3 Number of lane changes vs. number of through lanes

All simulation conditions were used to calculate coefficients in the prediction model. Results are shown in Table 5.4. Column B is the coefficients for all independent variables.

$$Y = a_0 + a_1 X_{12} + a_2 X_{13} + a_3 X_{14} + a_4 X_2 + a_5 X_3 + a_6 X_4 \qquad \text{Eq. (4)}$$

Where,

Y —— number of lane changes

X_{12} —— ramp type II

X_{13} —— ramp type III

X_{14} —— ramp type IV

X_2 —— freeway volume (vph)

X_3 —— exit rate (%)

X_4 —— number of thru lanes on freeway

Table 5.4 Coefficient values

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.062e+03	5.322e+01	-38.748	< 2e-16 ***
x12	4.556e+02	3.009e+01	15.139	< 2e-16 ***
x13	1.594e+02	3.009e+01	5.297	1.3e-07 ***
x14	6.095e+02	3.009e+01	20.252	< 2e-16 ***
x2	8.465e-01	1.845e-02	45.873	< 2e-16 ***
x3	3.309e+01	1.246e+00	26.552	< 2e-16 ***
x4	3.280e+02	1.303e+01	25.172	< 2e-16 ***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
Adjusted R-squared: 0.7327				

5.1.2 Average Speed

Comparisons of average speed among the four exit ramp types are shown from Figure 5.4 to Figure 5.6. In Figure 5.4, the exit rate is controlled by 20 percent, the number of thru lanes on the freeway is 3, and the average speed decreases with volume increasing. In Figure 5.5, the ramp exit rate changes from 5 percent to 30 percent, the number of thru lanes on the freeway is 3, and the average speed decreases with exit volume increasing. In Figure 5.6, the freeway volume is 800 vph, the ramp volume is 800 vph, and number of lane changes decreases with the number of thru lanes increasing. Thus, two independent variables have positive impacts on the number of lane changes, while the number of thru lanes has negative impacts. Under the same conditions, exit ramp type I has the largest average speed, and type IV has the smallest average speed.

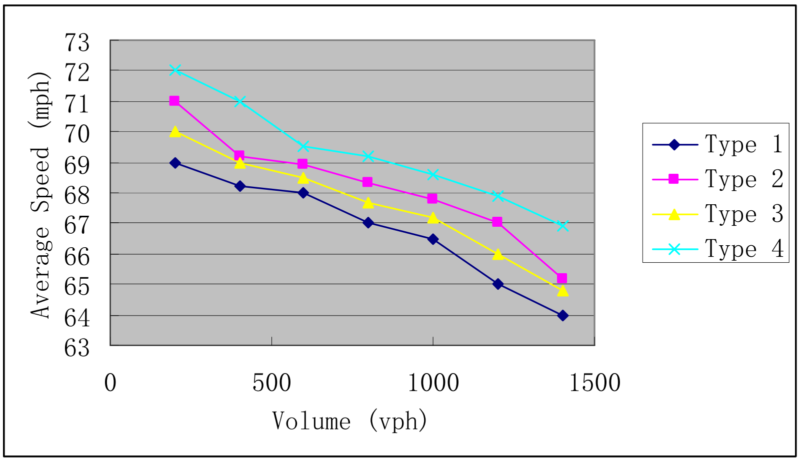

Figure 5.4 Average speed vs. volume

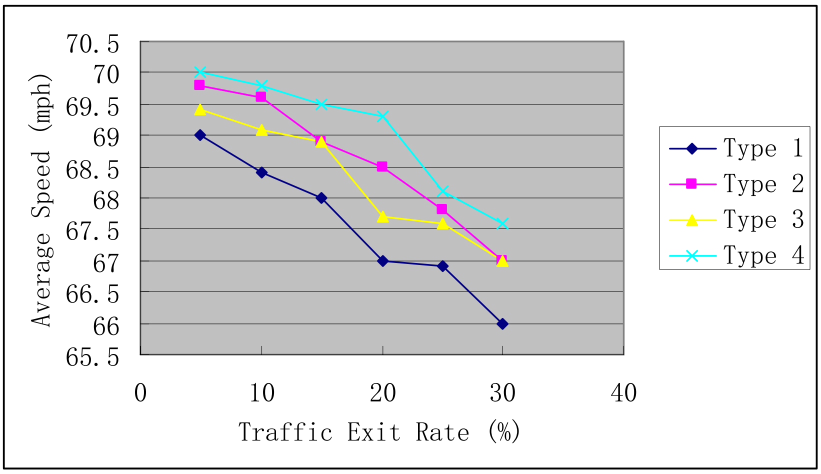

Figure 5.5 Average speed vs. traffic exit rate

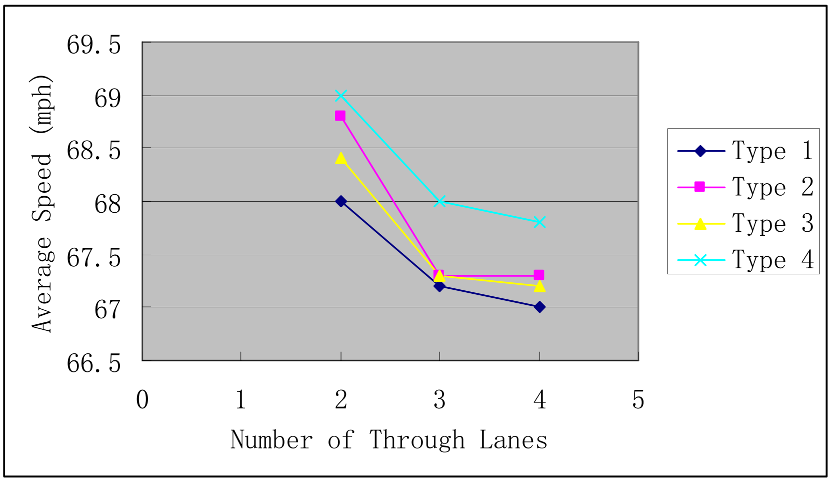

Figure 5.6 Average speed vs. number of through lanes

All simulation conditions were used to calculate coefficients in the prediction model. Results are shown in Table 5.5. Column B is the coefficients for all independent variables.

$$Y = a_0 + a_1 X_{12} + a_2 X_{13} + a_3 X_{14} + a_4 X_2 + a_5 X_3 + a_6 X_4 \quad \text{Eq. (5)}$$

Where,

Y —— average speed

X_{12} —— ramp type II

X_{13} —— ramp type III

X_{14} —— ramp type IV

X_2 —— freeway volume (vph)

X_3 —— exit rate (%)

X_4 —— number of thru lanes on freeway

Table 5.5 Coefficient values

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	72.1402683	0.3062959	235.5	< 2e-16 ***
x12	1.5794083	0.1732124	9.1	< 2e-16 ***
x13	1.2224556	0.1732124	7.1	2.6e-12 ***
x14	1.8364556	0.1732124	10.602	< 2e-16 ***
x2	-0.0026333	0.0001062	-24.795	< 2e-16 ***
x3	-0.0646289	0.0071717	-9.012	< 2e-16 ***
x4	-0.4882510	0.0750032	-6.5	1.0e-10 ***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
Adjusted R-squared: 0.7653				

5.1.3 Delay Time

The model for delay time is similar to the number of lane changes and average speed. All simulation conditions were used to calculate coefficients in the prediction model. Results are shown in Table 5.6. Column B is the coefficients for all independent variables.

$$Y = a_0 + a_1 X_{12} + a_2 X_{13} + a_3 X_{14} + a_4 X_2 + a_5 X_3 + a_6 X_4 \qquad \text{Eq. (6)}$$

Where,

Y —— delay time (s)

X_{12} —— ramp type II

X_{13} —— ramp type III

X_{14} —— ramp type IV

X_2 —— freeway volume (vph)

X_3 —— exit rate (%)

X_4 —— number of thru lanes on freeway

Table 5.6 Coefficient values

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-7.482e-01	1.335e-01	-5.606	2.4e-08 ***
x12	-4.273e-01	7.547e-02	-5.662	1.8e-08 ***
x13	-3.844e-01	7.547e-02	-5.093	3.9e-07 ***
x14	-5.274e-01	7.547e-02	-6.989	4.2e-12 ***
x2	6.937e-04	4.627e-05	14.991	< 2e-16 ***
x3	2.048e-02	3.125e-03	6.553	7.8e-11 ***
x4	1.619e-01	3.268e-02	4.955	8.0e-07 ***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
Adjusted R-squared: 0.6929				

5.1.4 Length Design for Deceleration Lane of Ramp Type I and IV

For the length design of the deceleration lane, ramp type I, the speed S.D. decreases quickly when length increases, especially when the volume is high. Figures 5.7 to Figure 5.12 show the speed S.D. vs. length under different volume levels.

However, for ramp type IV, this kind of change is not obvious. The speed S.D. decreases slowly when length increases, which means the deceleration lane does not have to be very long to lower speed S.D. It is also suggested that the length should be long if possible.

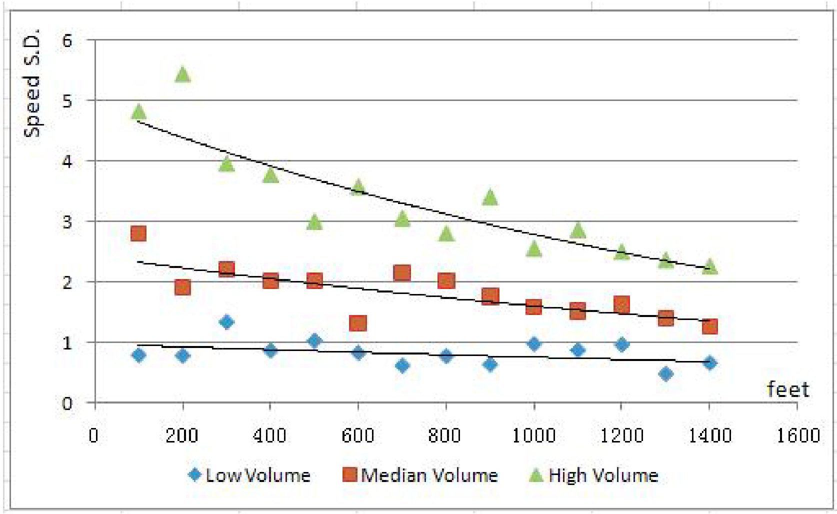

Figure 5.7 Speed S.D. vs. length (type I, 2 through lanes)

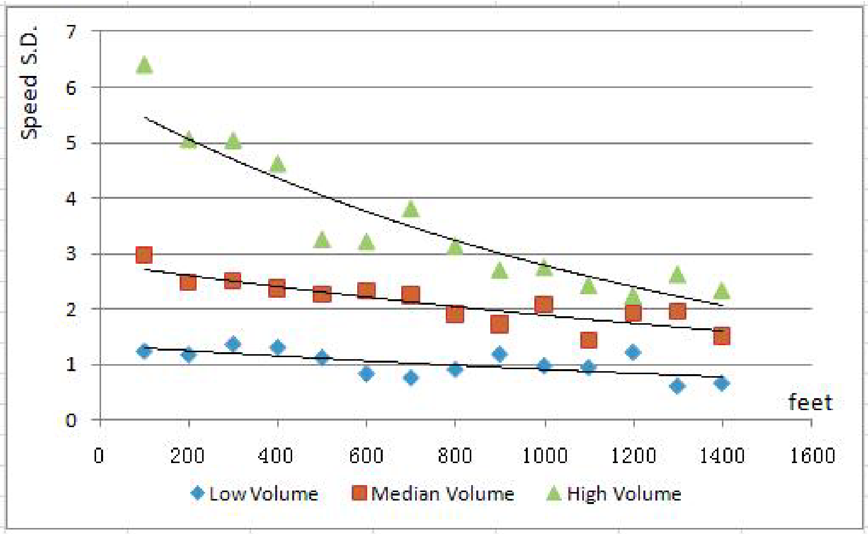

Figure 5.8 Speed S.D. vs. length (type I, 3 through lanes)

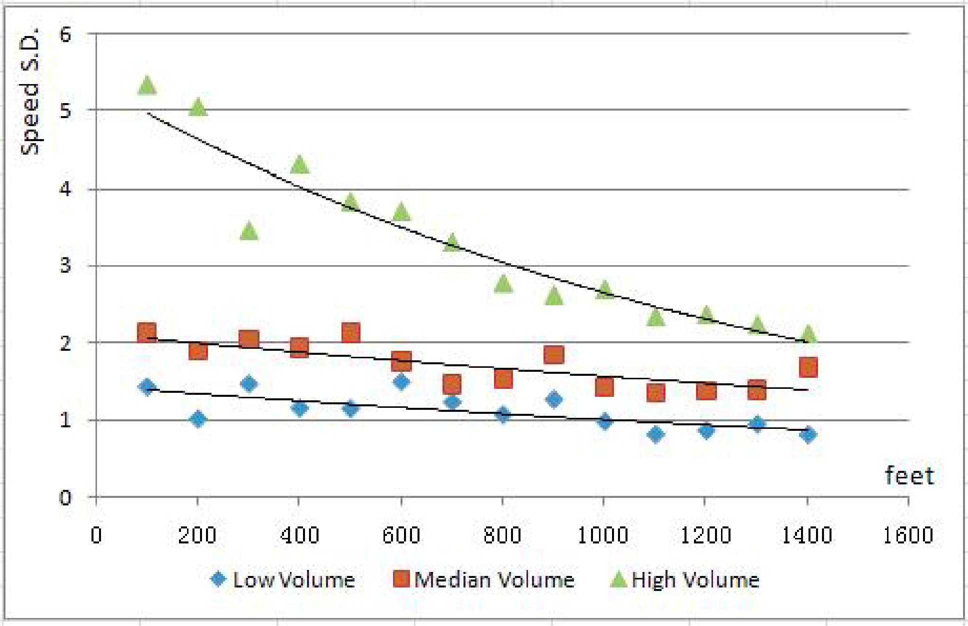

Figure 5.9 Speed S.D. vs. length (type I, 4 through lanes)

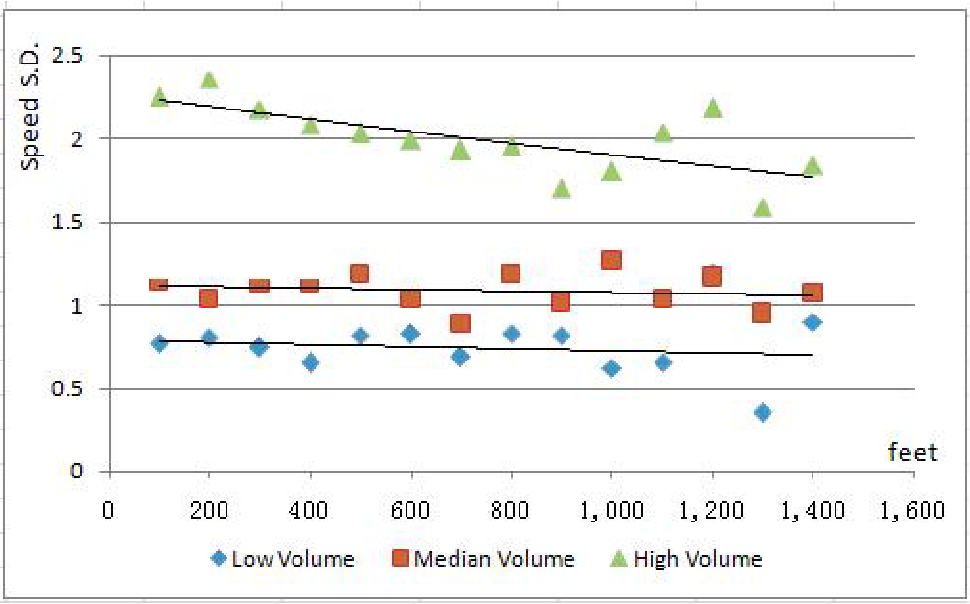

Figure 5.10 Speed S.D. vs. length (type IV, 2 through lanes)

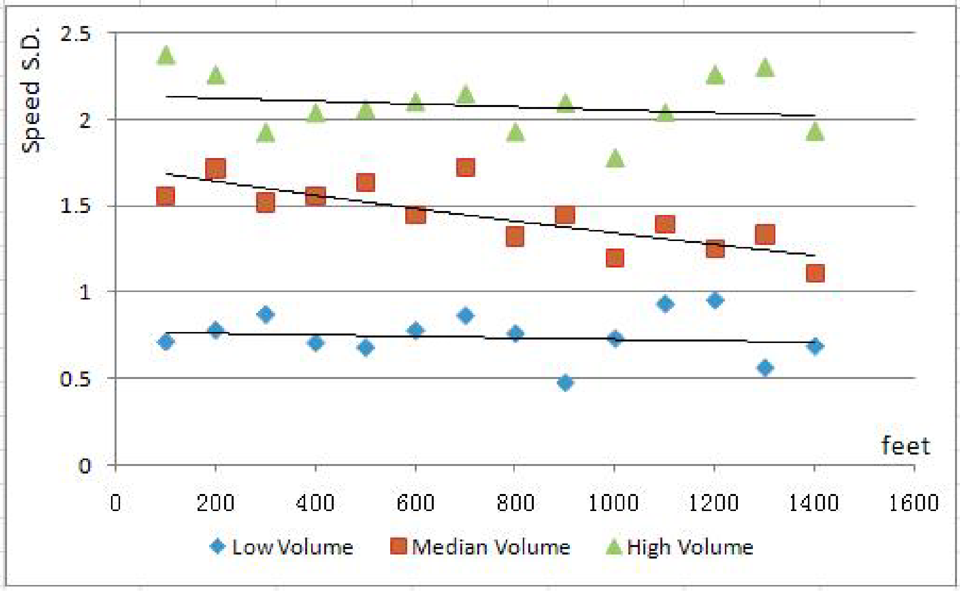

Figure 5.11 Speed S.D. vs. length (type IV, 3 through lanes)

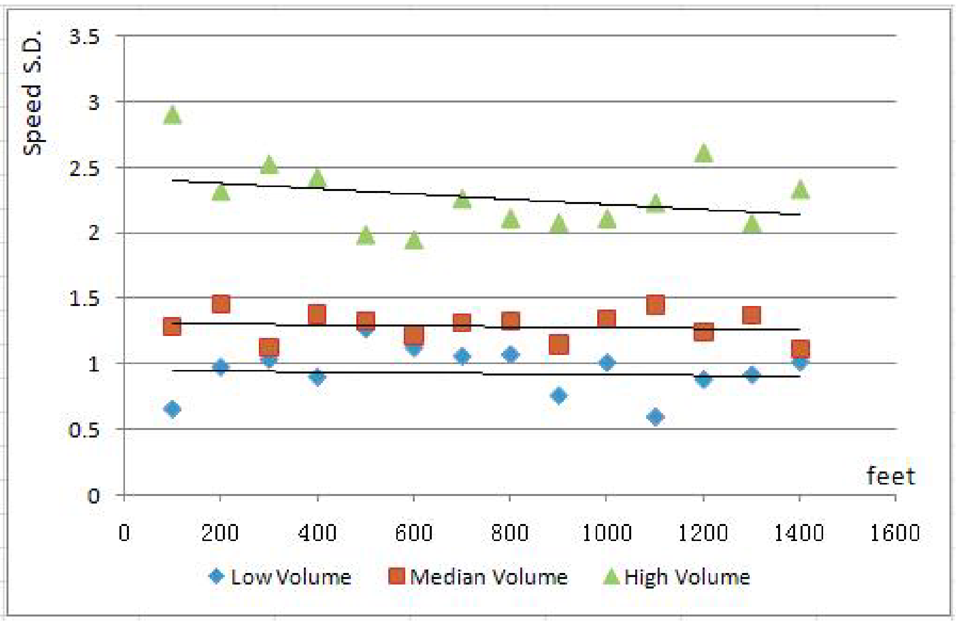

Figure 5.12 Speed S.D. vs. length (type IV, 4 through lanes)

The speed S.D. should be controlled under certain levels to research good operational performance. Simulation results are shown in Table 5.7, and simulation results are larger than the AASHTO standard.

Table 5.7 Minimum deceleration lane

Operating speed (mph)	AASHTO Standard (ft)	Simulation Type I (ft)	Simulation Type IV (ft)
55	480	750	550
60	530	800	600
65	570	850	650
70	615	875	700
75	660	900	725

5.1.5 Selection of Optimal Exit Ramp Type

The exponential models show different impacts of four types of ramps on the number of lane changes, speed SD, and control delay. The larger value of coefficient ai means more contribution of independent variable to dependent variable. Based on Tables 5.4, 5, and 6, a comparison table (Table 5.8) was developed to show the difference. It is clear that ramp type I has the least number of lane changes out of the four types, and type IV has the largest. For speed SD, the situation is the opposite: ramp type IV is the best, and type I the worst. For control delay, ramp type II is the best, and type I the worst.

Table 5.8 Comparisons of exit ramp types

MOE	Best → Worst
Number of Lane Changes	Type I → Type III → Type II → Type IV
Standard Deviation of Speed	Type IV → Type II → Type III → Type I
Control Delay per Vehicle	Type II → Type IV → Type III → Type I

Because the priority ranking of ramp type for each parameter is totally different, it is hard to say which is the optimal type of exit ramp; the importance of the three parameters is different under different conditions. For example, if expected exiting traffic for a ramp is very high, then the number of lane changes should be paid more attention in order to reduce crashes caused by decreasing lane changes. Or, in another case, if operational performance is required to strengthen, then control delay should be the first consideration. Thus, different weights can be added to the three parameters due to different design situations or requirements.

Taking ramp type I as the reference, coefficients of all other types can be compared based on the exponential model, as shown in Table 5.9. Take the second line of assigned weights (0.5 for lane change, 0.3 for speed SD, and 0.2 for control delay) as an example: the total value is 1 for ramp type I, 1.214 for type II, 1.057 for type III, and 1.276 for type IV. Therefore, ramp type I has the smallest value, and it is the optimal one under this condition.

The comprehensive evaluation model includes three MOEs (number of lane changes, average speed, and delay time per vehicle). Different weights for each MOE are assigned for different design conditions and considerations. Finally, the optimal one can be found. It is flexible for any necessary changes. Different MOEs can be added or deleted if available. Also, weights for each MOE can be changed.

Table 5.9 Selection of optimal exit ramp

Ramp Type	MOE	Relative a_i	Assigned Weights						
	Lane Change	1	0.33	0.5	0.5	0.3	0.3	0.2	0.2
I	Delay Time	1	0.33	0.3	0.2	0.5	0.2	0.5	0.3
	Ave. Speed	-1	0.33	0.2	0.3	0.2	0.5	0.3	0.5
Total Value for I			0.33	0.6	0.4	0.6	0	0.4	0
	Lane Change	1.19	0.33	0.5	0.5	0.3	0.3	0.2	0.2
II	Delay Time	0.94	0.33	0.3	0.2	0.5	0.2	0.5	0.3
	Ave. Speed	-1.08	0.33	0.2	0.3	0.2	0.5	0.3	0.5
Total Value for II			0.35	0.66	0.46	0.61	0.01	0.38	-0.02
	Lane Change	1.08	0.33	0.5	0.5	0.3	0.3	0.2	0.2
III	Delay Time	0.98	0.33	0.3	0.2	0.5	0.2	0.5	0.3
	Ave. Speed	-1.05	0.33	0.2	0.3	0.2	0.5	0.3	0.5
Total Value for III			0.34	0.62	0.42	0.61	-0.01	0.39	-0.02
	Lane Change	1.24	0.33	0.5	0.5	0.3	0.3	0.2	0.2
IV	Delay Time	0.91	0.33	0.3	0.2	0.5	0.2	0.5	0.3
	Ave. Speed	-1.12	0.33	0.2	0.3	0.2	0.5	0.3	0.5
Total Value for IV			0.34	0.67	0.47	0.6	-0.01	0.37	-0.04
Optimal Type			I	I	I	I IV	III IV	IV	IV

5.2 Exit Ramp Section

5.2.1 Ramp Length Design

Simulations for different conditions suggest different minimum ramp lengths, as shown in table 5.10. Table 5.11 compares field data to standard, and a red number shows field data that are shorter than standard. This table indicates that a short ramp length is an important problem in practical situations. Deceleration length is based on an average speed of 40 mph, and the distance is 200 ft for 50 mph and 225 ft for 60 mph.

Table 5.10 Minimum ramp length

No. of lanes on ramp	No. of lanes on cross road	No. of left turn bay	Queuing length (ft)	Deceleration length (ft)	Perception reaction length (ft)	Volume after queue (ft)	Total length (ft)
1	2	0	600	175	600	330	1705
1	4	0	850	175	600	415	2040
1	6	0	950	175	600	445	2170
1	2	1	550	175	600	315	1640
1	4	1	750	175	600	380	1905
1	6	1	900	175	600	430	2105
2	4	0	700	175	600	365	1840
2	6	0	875	175	600	420	2070
2	4	1	600	175	600	330	1705
2	6	1	800	175	600	400	1975

Note: Queuing length is based on simulation for observing sites during peak hour.

5.2.2 Ramp Configuration

Speed S.D. is selected for evaluating ramp configuration. D_1 and D_2 are changed in a range to see changes of speed S.D. Taking speed S.D. as reference 1, at D_1 it is less than 400ft, and D_2 it is at a level of 1600 ft. All other values are compared with 1. Based on this table, the longer the distance of D_1 and D_2 would cause the smaller the value of speed S.D., and the better performance.

Table 5.11 Observed ramp length

No.	Exit Ramp	Number of ThruLanes on crossroad	Ramp length (ft)
1	I-75 at State Road 56 - SB	4	2575
2	I-4 at County Road 579 - WB	2	1500
3	I-275 at Hillsborough Ave - NB	6	910
4	I-275 at Hillsborough Ave - SB	6	1100
5	I-75 at I-4 - SB	6	4300
6	I-275 at 4th St - SB	4	3950
7	I-4 at Universal Blvd - SB	6	2665
8	I-75 at CR 581 (BBD) - SB	6	2530
9	I-75 at Fowler Ave - SB	6	1750
10	I-4 at Lee Road -NB	6	1770
11	I-4 at Lee Road - SB	6	1840
12	I-4 at SR 434 - SB	6	1000
13	I-75 at State Road 56 - NB	6	2400
14	I-4 at County Road 579 - EB	4	1630
15	I-4 at Universal Blvd - NB	4	1630
16	I-4 at Conroy Road - NB	6	3800
17	I-4 at Conroy Road - SB	6	2415
18	I-4 at Altamonte Dr - NB	8	1050
19	I-4 at SR 434 - NB	4	1170
20	I-4 at Altamonte Dr - SB	8	800
21	I-75 at CR 581 (BBD) - NB	6	2600
22	I-75 at I-4 - NB	6	3900
23	I-275 at Ulmerton Rd - SB	4	3800
24	I-75 at Fowler Ave- NB	6	3800

Table 5.12 Relative speed S.D.

D_2 \ D_1	Type A: <=400	Type B: 600	Type B: 800	Type C: >=1000
1600	1	0.954	0.910	0.865
1800	0.987	0.941	0.904	0.853
2000	0.975	0.939	0.879	0.821

5.3 Crossroad Section

All simulation scenarios show results of minimum distance. The design minimum distance is tested under heavy traffic conditions, as shown in Tables 5.13 and 5.14.

Table 5.13 Minimum distance between ramp terminal and downstream intersection

Distance (ft)	Number of Lanes on Cross Road					
	2		4		6	
Weaving-moving across thru lanes	800		1200		1600	
Transition-moving into lanes	150 U	200 R	150 U	200 R	150 U	200 R
Perception-reaction distance	100 U	150 R	100 U	150 R	100 U	150 R
Storage	550 (200-300)		700 (200-300)		750 (200-300)	
Distance to centerline of intersection	40(50)		50(50)		60(50)	
Total distance	1640	1740	2200	2300	2660	2760

Note: U = Urban Area, R = Rural Area.

Table 5.14 Minimum distance between ramp terminal and upstream intersection

Distance (ft)	Number of Lanes on Cross Road					
	2		4		6	
Transition-moving into lanes	150 U	200 R	150 U	200 R	150 U	200 R
Perception-reaction distance	100 U	150 R	100 U	150 R	100 U	150 R
Storage	650 (200-300)		750 (200-300)		850 (200-300)	
Distance to centerline of intersection	40(50)		50(50)		60(50)	
Total Distance	940	1040	1050	1150	1160	1260

Note: U = Urban Area, R = Rural Area.

Chapter 6 Conclusions

This chapter represents simulation results and mathematical models to evaluate the operational performance of exit ramps. Comparisons are made to determine the optimal one. Ramp length and minimum distance on crossroads are also presented. Detailed conclusions are as follows:

- Numerical evaluations are provided for different ramp types on number of lane changes, average speed, and delay time. Three prediction models are presented.
- Minimum ramp length standard is presented based on analysis of speed S.D. by simulations. This standard is longer than the traditional one.
- A method for selecting the optimal exit ramp type is indicated. Different weights can be added due to different purposes. Optimal is not a constant, but type III and IV are suggested when traffic volume is heavy.
- Minimum exit ramp length is presented, which includes queuing length, movement distance, etc. This distance helps regulate future design.
- Simulation for ramp configuration shows that the longer distance between freeway and ramp terminal, and the longer distance between crossroad and exit ramp nose, the smaller the speed S.D. and the better the ramp operational performance.

- Minimum distance between ramp terminal and downstream/upstream intersections was calculated. This distance standard lowers speed variance and conflict and assures traffic mobility.

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