FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER

on Project

“Variable Speed Limit (VSL) – Best Management Practice”

FDOT Contract BDK77 977-11 (UF Project 00088592)

July 2012

Transportation Research Center
University of Florida

DISCLAIMER

METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS
TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

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16. Abstract

The Variable Speed Limit (VSL) system on the I-4 corridor in Orlando was implemented by Florida Department of Transportation in 2008, and since its deployment, it was revealed that the majority of traffic exceeds the speed limit by more mph when the speed limit is reduced versus when it is at the baseline level. The overall objective of this project was to gain a better understanding of the drivers' perception of the I-4 VSL system, to evaluate operations along the VSL zone of the I-4, and to investigate VSL strategies that have the potential to improve operations along I-4. Focus group studies as well as in-vehicle observation studies were conducted to evaluate driver perceptions. Participants indicated they would typically not reduce their speeds unless the drivers/motorists in their surroundings reduce theirs, and they suggested installing the VSL sign boards on both the sides of the roadway and, if possible, on the overhead sign boards at each lane. Through a combination of sensor data analysis and aerial reconnaissance, the research team identified bottleneck locations and congestion times. Based on these, a CORSIM simulation of the I-4 VSL zone was built in order to evaluate various potential VSL algorithms and their respective settings. It was concluded that changing the detector configuration and using the data from the worst performing detector have the potential to increase speeds and to improve operations for some of the VSL scenarios tested. A VSL system along I-4 may be able to provide some limited operational improvement at specific bottlenecks and/or along the entire network. However, there is no clear pattern regarding the type of algorithm that would be most beneficial at a particular bottleneck, nor any clear patterns regarding the VSL sign configuration.

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EXECUTIVE SUMMARY

The success of Variable Speed Limit (VSL) zones in European countries and here in the United States is attributed to many factors and strategies that have been operationally implemented after the established and subsequent qualitative assessment of the various VSL systems goals and objectives. VSL systems that are implemented for roadway and weather conditions seem to have better driver compliance than a system designed to reduce traffic congestion and the “accordion effect”. A recent study of FDOT District 5 VSL on the 10-mile stretch of I-4 from Orange Blossom Trail to Maitland Boulevard in downtown Orlando indicated that the majority of traffic exceeds the speed limit by more mph when the speed limit is reduced versus when it is at the baseline level. The study results also indicated that the VSL system, as currently operating on I-4, is not improving the traffic safety in terms of rear-end collisions. The data from this study suggested that the full benefits of the VSL system cannot be accurately evaluated because the motorists are simply not complying with the reduced speeds. Therefore, the VSL system never has the chance to reach the full potential it was designed to accomplish.

The following activities were conducted throughout this project.

Focus Group Studies: A total of 24 participants were recruited to participate in three focus groups and share their perception of the existing VSL system. The participants strongly recommended that the VSL system and its benefits should be promoted to the general public through the use of various media such as fliers, local news TV, internet, and radio. They also indicated that they would typically not reduce their speeds unless the drivers/motorists in their surroundings reduce theirs, and they suggested installing the VSL sign boards on both the sides of the roadway, and if possible, on the overhead sign boards at each lane.

In-Vehicle Data Collection: A total of 15 participants were recruited to drive the Transportation Research Center’s (TRC) instrumented vehicle in order to gather driver behavior data along the VSL zone. Generally the participants’ behavior was consistent with the conclusions from the focus group study. Furthermore, it was determined that the displayed speed limit is often higher than the prevailing conditions, and at some locations the speed limit displays

reduced values when the freeway is at free-flow speed. A potential issue may be the accuracy of the detector just before the exit to Amelia Street. It appeared that the occupancy values being relayed by this detector were too low for the prevailing speeds.

I-4 VSL Zone Assessment and Bottleneck Identification: This task used the I-4 corridor sensors' speed and flow data to identify bottleneck locations along the eastbound and westbound directions of I-4. The on-ramp from SR-408 onto I-4 EB was found to be the major source of congestion along the eastbound direction during the AM and PM peak. During the PM peak, the on-ramps from Maitland Boulevard and Fairbanks Avenue were found to trigger congestion as well. The source of congestion along the I-4 WB direction was found to be outside the VSL zone, downstream of the on-ramps from Lake Mary Boulevard, SR-434, and Altamonte Springs.

Aerial Reconnaissance: The research team conducted an aerial reconnaissance along the I-4 VSL corridor to observe and confirm the bottleneck locations and effects of the VSL system. A flight company was hired to carry out aerial flights, and twenty hours of aerial observations were recorded along the I-4 corridor. The I-4 WB direction was not found to be congested during the morning hours on the section where the current VSL system exists. The westbound direction was found to be congested at the interchanges near Altamonte Springs, SR-434, and Lake Mary Boulevard. The I-4 EB direction was found to be congested recurrently between 7:20 AM and 7:30 AM at the section where the on-ramp from SR-408 joins I-4 EB resulting in long queues up to Kaley Street.

Development of Operational Improvements and Recommendations: A CORSIM simulation model of the I-4 VSL zone was built in order to evaluate various potential VSL algorithms and their respective settings. The scenarios evaluated pertain to changes in the VSL algorithms, sign locations, detector locations, as well as an evaluation of the impact of driver compliance on traffic operations. First, the current I-4 VSL algorithm was modeled in CORSIM and calibrated to replicate existing operations. Different scenarios were evaluated considering three different VSL algorithms, various VSL sign location scenarios, different detector locations, and two levels of driver compliance. With the current VSL configuration of signs and detectors, there was no observed operational improvement, and when VSL control was removed, speeds were slightly higher than the VSL scenarios. However, changing the detector configuration and using the data from the worst performing detector have the potential to increase speeds and to improve operations for some of the VSL scenarios tested. It was concluded that a VSL system along I-4 may be able to provide some limited operational improvement at specific bottlenecks and/or along the entire network. However, there is no clear pattern regarding the type of algorithm that would be most beneficial at a particular bottleneck, nor any clear patterns regarding the VSL sign configuration.

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1 INTRODUCTION

1.1 Background

The success of Variable Speed Limit (VSL) zones in European countries and here in the United States is attributed to many factors and strategies that have been operationally implemented after the established and subsequent qualitative assessment of the various VSL systems goals and objectives. VSL systems that are implemented for roadway and weather conditions seem to have better driver compliance than a system designed to reduce traffic congestion and the "accordion effect". A recent study of FDOT District 5 VSL on the 10-mile stretch of I-4 from Orange Blossom Trail to Maitland Boulevard in downtown Orlando indicated that the majority of traffic exceeds the speed limit by more mph when the speed limit is reduced versus when it is at the baseline level. The study results also indicated that the VSL system, as currently operating on I-4, is not improving the traffic safety in terms of rear-end collisions. The data from this study suggested that the full benefits of the VSL system cannot be accurately evaluated because the motorists are simply not complying with the reduced speeds. Therefore, the VSL system never has the chance to reach the full potential it was designed to accomplish.

The overall objective of this project is to gain a better understanding of the drivers' perception of the I-4 VSL system. Furthermore, the project investigated various VSL strategies that have been implemented in other states and/or countries and have produced positive results in dealing with traffic congestion, speed limit compliance, and reduced rear-end crashes. Although previous studies or implementations have demonstrated that VSLs lead to substantial safety benefits, there is no clear empirical evidence on the aspect of improved efficiency or congestion mitigation. There is also no "VSL Best Management Practices" document that traffic engineers and freeway systems operators can reference to maximize the benefits of such an application.

1.2 Report Organization

The objectives of the current study are to: a) identify and describe VSL operational strategies that have resulted in improvement in mobility and/or safety; b) gain a better understanding of the drivers' perceptions of the VSL; c) gain a better understanding of the operations and bottleneck locations along the I-4 corridor where the VSL is implemented; and d) develop recommendations for improvements related to the VSL system and other traffic control devices along the I-4 corridor to improve traffic operations.

To achieve the objective of this study, the following activities were carried out:

- **Literature Review:** The research team conducted a thorough literature review to identify and describe the existing VSL operational strategies in the U.S. and in other countries. This literature review is provided in Appendix A of this report.
- **Focus Group Studies:** The research team conducted focus group sessions by recruiting frequent travelers along I-4 corridor to solicit drivers' perceptions and opinions on the VSL system. The process and results of this activity are discussed in Chapter 2.
- **In-Vehicle Data Collection:** To supplement the focus group studies, the research team conducted in-vehicle experiments during which participants were asked to drive along the VSL zone and their behavior was monitored and analyzed. This activity and the resulting conclusions are provided in Chapter 3.
- **I-4 VSL Zone Assessment and Bottleneck Identification:** The research team obtained the speed flow traffic data from the sensors located along the I-4 VSL zone to identify the recurring bottleneck locations. The details of the data analysis along with a list of all bottleneck locations along the I-4 corridor are provided in Chapter 4.
- **Aerial Reconnaissance:** The research team performed an aerial observation of the traffic operations along I-4 when the VSL system is activated. The aerial videos recorded from a helicopter were reviewed to confirm the bottleneck locations as identified in the previous task and observe the key locations and causes of congestion along the VSL zone. An overview of this activity and its results are provided in Chapter 5.
- **Development of Operational Improvements and Recommendations:** The research team built a CORSIM simulation model of the I-4 VSL zone, and evaluated several alternative scenarios. The details of all the alternate scenarios and the results are provided in Chapter 6.

2 FOCUS GROUP STUDIES

The objective of the focus group study was to obtain drivers' perceptions and opinions on the VSL system through group discussions/meetings. To accomplish this objective, the following activities were performed by the research team: recruiting participants for the focus group meetings; preparing questions to spur the discussions with the participants during the meetings; and summarizing the participants' responses, perceptions and opinions regarding the VSL system.

Before recruiting the participants for the focus groups, the research team required approval from the Institutional Review Board (IRB) at the University of Florida to conduct such meetings. The IRB is a committee designated to approve, monitor, and review biomedical and behavioral research involving humans. Since human subjects were involved in the study, such approval was required. The paperwork included a research application to the IRB for the approval of the research with human subjects, an informed consent for the participants (that lists the risk factor in the study), a prescreening and background questionnaire (to select a diverse pool of participants for the study), and an advertisement for recruiting the participants. These documents which were submitted to the IRB for their approval are provided in Appendix B. Upon IRB approval, the research team advertised the study through different media sources. The next section describes the recruitment procedure.

2.1 Recruiting Participants

To recruit participants, the research team considered several potential options for advertising the study. Since it was most desirable to recruit frequent I-4 travelers in Orlando, posting an advertisement on Orlando's Craigslist website and in any classified section of a daily newspaper in Orlando seemed to be most appropriate. Before posting the advertisement at any level, the research team designed a website for the study. The website included details of the study, the purpose, and other recruiting related information. The website is available at https://sites.google.com/site/i4vslsystem. A snapshot of this website is also provided in Appendix B.

After the website was developed, the advertisement for the recruitment was posted online at Orlando's Craigslist under it's volunteers section. The first advertisement was posted at the end of December 2010. A brief description of the study was provided, and through this advertisement, candidates were asked to fill out a prescreening questionnaire available at http://tinyurl.com/37ztbls. The motivation behind the prescreening questionnaire was to provide a mechanism for selecting a diverse pool (socio-economically and demographically) of participants for the study. The advertisement also included the link to the focus group study website.

In the first two weeks, only a limited number of candidates expressed interest in the study and filled out the prescreening questionnaire. The number of candidates gradually increased as the advertisement was posted regularly on Orlando's Craigslist website. By the end of January 2011, 47 candidates completed and submitted the prescreening questionnaire. The responses from these candidates were analyzed, and it was observed that most of the candidates fell into the category of either a student and/or income less than $40,000. Therefore, it was felt that a diverse pool of participants may not be recruited through the Craigslist advertisement.

In an attempt to obtain more diversity in the pool of participants, the research team posted a recruitment advertisement in the newspaper daily Orlando Sentinel. The advertisement was published in the Orlando Sentinel Classifieds section for four days, from 11th-13th February 2011 and on 17th February 2011, and in the online section of the Classifieds from 11th February 2011 until 18th February 2011. It was expected that with the help of this advertisement, a more diverse pool of participants could be selected for the study. Unfortunately, even the advertisement in the Orlando Sentinel did not attract many candidates. Therefore, the research team decided to continue posting the advertisements on the Craigslist website until a more diverse pool of candidates was obtained.

By 4th March 2011, a total of 89 candidates completed and submitted the prescreening questionnaire, and participants with income more than $40,000 were found to be interested in the study. With these candidates, it was felt that a diverse pool of participants could be recruited for the study. After analyzing the candidates' responses, a total of 32 candidates were selected for these focus group meetings. The primary criteria for selecting these candidates were their awareness of the VSL system, frequency of travel on I-4, and diversity of socio-economic and demographic factors. The participants were divided into three diversified groups with 11, 10, and 11 candidates.

While the advertisements were posted, the research team planned to conduct these meetings on 12th March 2011 at the FDOT District 5 Urban office in Orlando. Three time slots; 9AM – 11 AM, 12 PM– 2 PM, and 3 PM – 5 PM, were chosen for conducting these meetings. The selected candidates were notified with the location of these meetings and their respective time slots. The research team also prepared a list of questions to spur the discussion on the VSL system during the focus groups. The questions are provided in Appendix B (additional questions may have been asked depending on the nature of the group discussions). The next section describes the proceedings of the focus group meetings, and provides a detailed summary of the discussions with the participants.

2.2 Focus Group Meetings

On the day of the focus group meetings, i.e. 12th March 2011, only 6, 10, and 8 participants for the respective time slots appeared to participate in the study. Even with less than the expected number of participants for each time slot, the research team decided to continue with the proceedings of the focus groups. Appendix B provides a summary of the demographic and socio-economic factors of the participants that appeared for each focus group.

Before the start of each meeting, the research team discussed the procedure and purpose of the focus groups. At first, the research team showed a video clip of I-4 traffic that was recorded a day earlier on 11th March 2011 along theI-4 corridor between Orange Blossom Trail and East-West Expressway. The recording included the instance when the VSL signs were activated along I-4 corridor. The motivation was to confirm that everyone in attendance was indeed familiar with the VSL signs and that this was the general subject of discussion for the meeting, as well as to provide a starting point for the discussion.

After the video recording was played, the focus group meetings were initiated. During the focus group meetings, the research team discussed the following aspects of the VSL system with the participants:

- the participants’ awareness of the VSL system;
- the visibility of the VSL sign boards;
- the participants’ driving response when encountering the VSL sign boards; and
- their suggestions to make the VSL system more effective.

The entire duration of each focus group meeting was audio-recorded. A summary of these audio recordings is provided next (the opinions expressed in the following paragraphs are solely from the focus group participants, and not the research team).

First, the research team asked the participants about their awareness of the VSL system. During the discussion, most of the participants indicated that they were aware of the fact that it is primarily used to control the downstream traffic flow, and to enhance the safety of the drivers along I-4. The participants also indicated that the VSL system is an alternate way of alerting the commuters of downstream congestion. On the other hand, a few participants were unaware of the purpose that the VSL system intends to serve. They indicated that they thought the VSL system is primarily intended to slow the traffic flow before entering the sections of I-4 with sharp horizontal curvature. When asked if the participants were informed about the implementation of the VSL system in 2008, most of them indicated that they did not hear about the system from any government or transportation agencies. These sets of participants also stressed that they had little knowledge on the purpose and the benefits of the VSL system when it was initially deployed. Among all the participants in the three groups, only one claimed to have read about the VSL system through an FDOT website.

Second, the research team asked the participants about their typical driving response when they observe a change in speed limit or reduced speed limits along the VSL stretch of I-4. To this, most of the participants in all three groups indicated that they would not change their driving speeds and they feel more comfortable in maintaining a speed similar to the rest of the vehicles in their local surroundings, which they admitted was typically higher than the posted speed limits. According to the participants, slowing down their vehicle would mean that everyone else around them would pass them and they would consider themselves as an obstacle on the freeway and less safe. These opinions were generally expressed by the younger participants. On the contrary, the older drivers (above 45 years), as well as a couple of younger drivers, indicated that they would follow the speed limits and will change their speeds accordingly, but at the same time they are cautious of the faster vehicles around them. Most of the participants indicated that by the time they enter the active VSL zone or they realize the speed limit has been reduced, they found themselves in congestion, where changing or reducing speeds at that time would no longer make a difference. In general, the consensus of the participants was that they would only reduce their speed if everyone else in their surroundings similarly reduces their speed. This led to another discussion that focused on the lower speed limits used in the VSL zone during the non-congested periods. The participants suggested that the speed limits during the night time or anytime of the day when the traffic demand is low should be increased from 50-55 mph to a minimum of 60-70 mph.

Third, the research team asked the participants about their opinions on the visibility and the size of the VSL sign boards. To this, the first group responded by saying that the VSL signs are visible from both the leftmost and the rightmost lanes on I-4, and they do not have any problems with the sign boards. On the contrary, the other two groups felt that the sign boards were not visible from the leftmost lane except for the locations where the sign boards are present on both shoulders and medians. The second and third group participants felt that the positioning of the sign boards may not be appropriately located because there are times of the day when the displayed speed limits are either not visible due to sunlight or the presence of trucks in the rightmost lanes obstruct their view. However, all three groups suggested that the VSL sign boards should be placed on both sides of the road, i.e. at shoulders and on the medians. They cited examples of the VSL sign boards placed at Orange Blossom Trail and at Maitland Blvd (where sign boards are placed on shoulders and medians), and indicated that these locations are most appropriate for displaying reduced speed limits.

Fourth, the research team asked the participants how they feel about the prospect of automated speed enforcement along the VSL zone. To this, most of the participants responded that the presence of law enforcement would compel them to follow the speed limits, as they would be more cautious about their speeds knowing they are monitored. At the same time, a few participants indicated that even with the presence of law enforcement they would prefer to go along with the traffic flow because the chances of getting a speeding ticket will probably decrease as everyone else on the roadway will maintain the higher speeds.

Last, the research team asked the participants if they have any other opinions on I-4 traffic, and not necessarily related to the VSL system. Several different issues were raised during this discussion. First, the participants were concerned about the horizontal curvature of I-4 at the location downstream of Fairbanks Avenue in the eastbound direction and at Ivanhoe Blvd in the eastbound direction. According to them, the horizontal curvature often results in dramatic speed reduction, and is the primary cause for an accident. Second, the participants indicated that the length of the off-ramps from I-4 EB to East-West Expressway (SR-408) and to Kaley Street is too short, and congestion is observed very frequently. Last, a couple of participants suggested that the I-4 WB section between Lake Mary and Maitland is consistently found to be congested during the morning hours because of high on-ramp traffic joining the I-4 corridor. A detailed summary of all the questions and the participants' responses by each group are provided in Table 2.1.

To close each focus group session, the research team briefly explained the traffic flow theory behind the VSL system and its potential benefits to all the participants. As the participants understood the logic behind the implementation of the VSL system, they were given the opportunity to express their thoughts on how this system could be improved and what measures would encourage them to abide by the displayed speeds in the VSL zone. These suggestions and recommendations are summarized in the next subsection.

2.3 Suggestions/Recommendations

After the discussions were concluded, several recommendations were suggested by the participants. These are:

Table 2.1 Detailed summary of the focus group meetings participants' responses

Questions	**Focus Group 1**	**Focus Group 2**	**Focus Group 3**
1) Are you aware of the purpose that the VSL system is intended to serve?	a) To control traffic, and improve the traffic flow. b) It is a system to enhance drivers' safety.	a) To control traffic and prevent further congestion b) To reduce accidents.	a) To regulate traffic, and prevent the vehicles from joining the congestion. b) The normal speed limits are too fast for the horizontal terrain; as a result, the speed limits are lowered.
2) What would be your typical driving response when you see a change in speed limit?	a) It would depend on the traffic condition around. b) If nobody pays attention, then will not change the speed and go along with the same speed. c) It is hard to keep a lower vehicular speed, hence will change lanes and pass the neighboring vehicles.	a) Would not change speed unless the other vehicles around do so. b) Would try to follow the changing speed limits*.	a) Would go along with the flow, and not necessarily slow down. b) Will be alerted, and reduce speed*.

Questions	**Focus Group 1**	**Focus Group 2**	**Focus Group 3**
3) Are the installed VSL sign boards visible to you?	a) The signs are visible from both outside and inside lanes. b) The VSL signs are more visible from inside lanes. Due to heavy traffic, or presence of trucks on right lane, it is difficult to see them through outside lanes. c) Did not see the flashing beacon lights when speeds were below 50 mph.	a) Not visible from inside lanes. b) Will be effective if speed limits are displayed on an overhead sign board. c) Flashing beacons do not work when lower speed limits are displayed.	a) The sign boards on both sides of I-4 are visible. b) The size and height of VSL sign boards is too small, so they are not clearly visible. c) The color combination of displayed speed limits should be changed.
4) Did you hear about the VSL system through any kind of media advertisement?	a) There has never been an announcement, or any advertisement on the VSL system. b) Advertisement seen on a web-page created by FDOT*.	a) Did not hear about the VSL system through any means of communication.	a) Heard about changes on I-4 through radio and news channel, but not about VSL system. b) Most of the Orlando commuters are unaware of the system.

Questions	**Focus Group 1**	**Focus Group 2**	**Focus Group 3**
5) How would you feel about the prospect of automated speed enforcement?	a) With automated speed enforcement, the speed limits would be followed. b) Virtual speed enforcement could also arouse fear in drivers' driving behavior.	a) It would arouse fear among drivers, and they would follow speed limits.	a) Would follow speed limits, even if it is 30 mph. b) Would get more cautious about changing speed limits
6) Do you have any suggestions for the current VSL system?	a) The VSL system should be advertised through different media like news, daily newspaper, Facebook, mobile apps, along with its benefits. b) VSL system should be extended over to regions with tourist activities in Orlando. c) The VSL could be displayed on Dynamic Message Sign (DMS) boards. d) The speed limits should change after the beacons have flashed for a certain amount of time. This will warn the drivers about the changing speed limits.	a) The benefits of the VSL system should be publicized. b) The VSL system should be extended from Conroy Road until Lake Mary Blvd. c) Speed limits should be displayed on overhead sign boards. d) FDOT should install 'STOP' or 'Red Light' signs over on-ramps to control traffic on I-4*.	a) Commuters should be educated on VSL benefits. b) More enforcement will lead to more commuters following the system. c) Install advance warning signs before entering the VSL zone. d) Tourists should be made aware of the existing VSL system in Orlando.

*Indicates responses by only one participant among the entire group

- The participants strongly recommended that the authorities should promote the VSL system and its benefits to the general public through the use of various media such as fliers, local news TV, internet, and radio. The participants emphasized educating the commuters on the benefits of the VSL system.
- In general, the participants preferred to have the VSL sign boards on both sides of the roadway. They also felt that by displaying the speed limits directly over the lane on an overhead sign board, they will be more alerted on the reduced speed limits.
- The participants suggested that an advanced warning message should be displayed on the dynamic message sign boards to alert the commuters to the upcoming reduced speed limits. They indicated that the current beacon lights should be maintained properly, and should be installed at frequent locations.
- The participants suggested that the authorities should control the on-ramp traffic joining the I-4 mainline.
- The participants were generally accepting of the use of automated law enforcement along I-4 if that would promote greater compliance with the reduced speed limits.

2.4 Summary

The research team conducted focus group meetings to obtain the drivers' perspective and opinions on the VSL system by recruiting frequent commuters along the I-4 corridor. Three sessions that involved 6, 8 and 10 participants were conducted on 12th March 2011 at the FDOT District 5 Urban Office in Orlando, FL. During the focus group meetings, the research team discussed several aspects of the VSL system with the participants. The responses, opinions, and the recommendations/suggestions of the participants from the study were summarized and reported.

3 IN-VEHICLE DATA COLLECTION

3.1 Introduction

During Task 2, the research team selected participants to drive the his part of the study supplemented the focus group findings and was conducted to observe how drivers actually behaved in the presence of VSL signs.

The instrumented vehicle used has four cameras that can monitor the traffic conditions surrounding the vehicle. Various vehicle characteristics such as speed, acceleration, and location are continuously monitored and the data are stored on the hard drive located within the vehicle. Fifteen subjects were solicited to drive the instrumented vehicle along the I-4 VSL zone. The subjects had no prior knowledge of the intent of the experiments to avoid bias. After the subjects completed their driving task they answered a post-driving questionnaire regarding their driving experience and their perception of the VSL system.

The process and results of the experiment are discussed in the remainder of this chapter. Section 3.2 describes the experiment and the recruitment of subjects. Section 3.3 presents the resulting plots that display the subjects' driving speed vs. the displayed speed limit over the entire VSL zone. Section 3.4 discusses the results of the post-driving questionnaire. A brief summary of the overall findings and conclusions is presented in section 3.5.

3.2 Description of the Experiment

All appropriate Institutional Review Board (IRB) approvals for the participation of human subjects were obtained prior to conducting these experiments. A total of 15 participants were recruited through a craigslist advertisement, and each participant selected was compensated $50. The participants were asked to fill out a survey before being considered for the study. The background information of the selected participants is provided in Table 3.1. If the participants qualified for the study a date was scheduled to perform the experiment. Participants were scheduled to drive on a regular weekday (Tuesday through Thursday) during typically congested conditions (6:30 – 10:00 AM or 4:00 – 7:00 PM).

Table 3.1 Participants' background information

	Gender	Age range (years)	Race	Driving experience in the U.S.?
Subject 1	Male	40-49	Caucasian	10+ years
Subject 2	Male	40-49	Caucasian	10+ years
Subject 3	Female	20-29	Hispanic	3 to 9 years
Subject 4	Male	30-39	Hispanic	10+ years
Subject 5	Male	30-39	Caucasian	10+ years
Subject 6	Female	20-29	Asian	3 to 9 years
Subject 7	Female	20-29	Caucasian	3 to 9 years
Subject 8	Female	20-29	Caucasian	3 to 9 years
Subject 9	Male	50-59	Caucasian	10+ years
Subject 10	Male	20-29	Hispanic	10+ years
Subject 11	Female	20-29	African American	10+ years
Subject 12	Female	50-59	Caucasian	10+ years
Subject 13	Female	20-29	Caucasian	3 to 9 years
Subject 14	Female	20-29	Caucasian	3 to 9 years
Subject 15	Female	20-29	Hispanic	3 to 9 years

Driving experiments were scheduled to coincide with peak traffic conditions in the AM and PM. Before each experiment the participant completed a background survey to assess their driving habits. The results of this survey are provided in Table 3.2. The drivers were not informed that the experiment was focused on the VSL system; they were told that this experiment was to assess freeway management along I-4, and were asked to drive a specified distance on I-4 like they normally would. Each participant started driving experiment at Conroy Rd. and drove eastbound on I-4 until Maitland Blvd. They then exited the freeway and re-entered going westbound, finally exiting at Conroy Rd. A map of the driving route is shown in Figures 3.1, 3.2, and 3.3.

During the experiment, the following were recorded: video, audio, speed and GPS coordinates. The researchers in the vehicle recorded the displayed speed limit for every sign location. After driving was completed, the participants completed a questionnaire related to their driving experience as well as their perception and understanding of the VSL system.

Table 3.2 Participant driver type information

	What type of driver do you consider yourself?	**What type of driver do your friends/family consider you?**	**If the speed limit is 70 mph what speed are you likely to drive?**	**How often do you change lanes if the vehicle in front of you is slower?**	**Average Desired Speed (from field data)**	**Discretionary lane changes per mile (from field data)**
Subject 1	Somewhat conservative	Somewhat conservative	65 to 70 mph	Sometimes	NA	NA
Subject 2	Somewhat conservative	Somewhat conservative	65 to 70 mph	Sometimes	NA	NA
Subject 3	Somewhat conservative	Somewhat aggressive	75 to 80 mph	Very often	NA	NA
Subject 4	Somewhat conservative	Somewhat conservative	70 to 75 mph	Sometimes	NA	NA
Subject 5	Somewhat aggressive	Somewhat aggressive	75 to 80 mph	Very often	NA	NA
Subject 6	Somewhat conservative	Somewhat conservative	70 to 75 mph	Very often	NA	NA
Subject 7	Somewhat aggressive	Somewhat aggressive	75 to 80 mph	Very often	NA	NA
Subject 8	Somewhat conservative	Somewhat conservative	75 to 80 mph	Very often	NA	NA
Subject 9	Somewhat conservative	Somewhat conservative	70 to 75 mph	Sometimes	NA	NA
Subject 10	Somewhat aggressive	Somewhat aggressive	65 to 70 mph	Sometimes	NA	NA
Subject 11	Somewhat aggressive	Somewhat aggressive	70 to 75 mph	Very often	NA	NA
Subject 12	Somewhat conservative	Somewhat conservative	65 to 70 mph	Very often	NA	NA
Subject 13	Somewhat aggressive	Somewhat conservative	70 to 75 mph	Very often	NA	NA
Subject 14	Somewhat conservative	Somewhat conservative	70 to 75 mph	Very often	NA	NA
Subject 15	Somewhat aggressive	Somewhat aggressive	75 to 80 mph	Very often	NA	NA

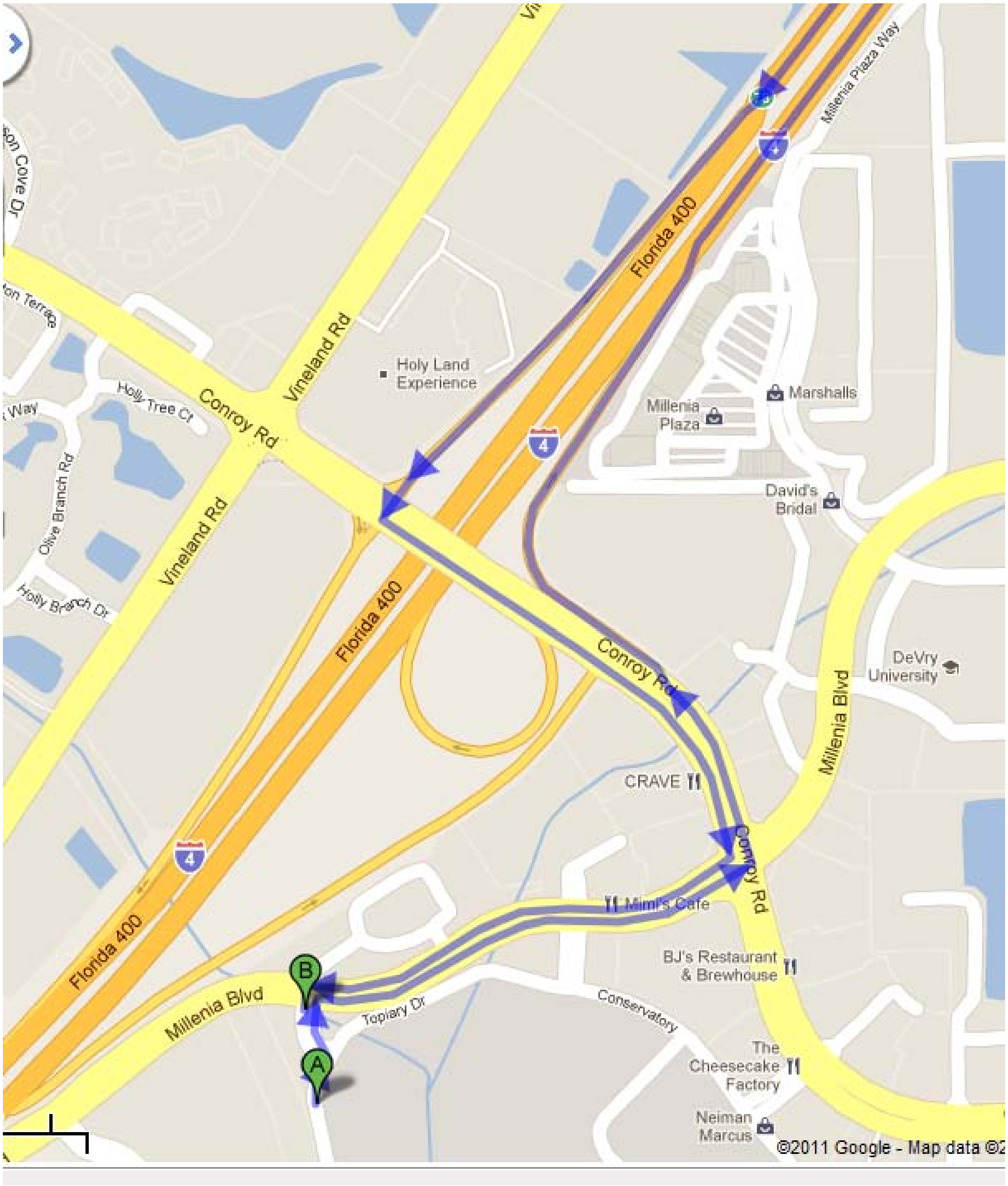


Figure 3.1 Map of driving route (beginning and end)

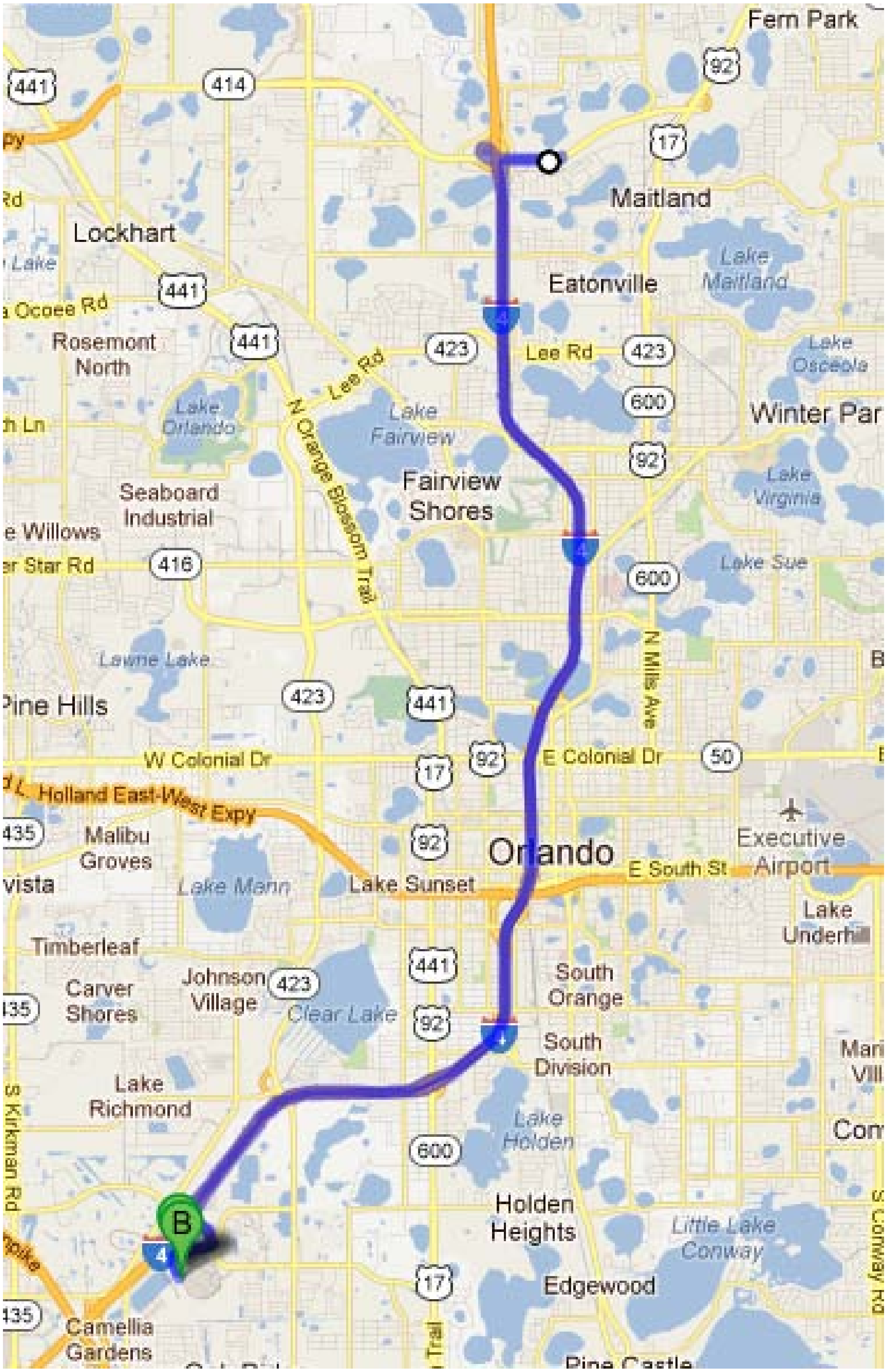


Figure 3.2 Map of driving route (overview)

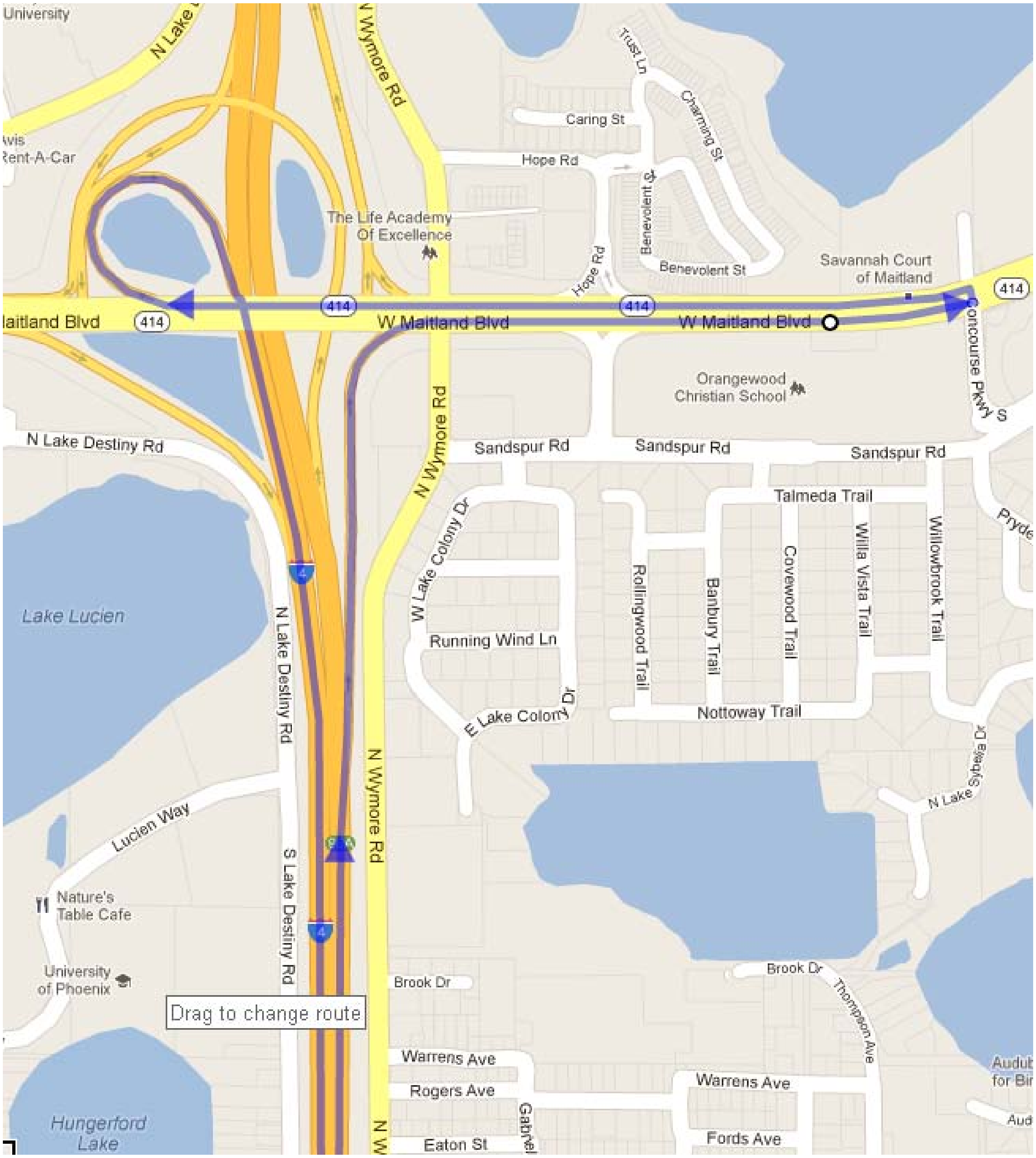


Figure 3.3 Map of driving route (turnaround)

3.3 Participants' Speed vs. the Displayed Speed Limit

Table 3.3 summarizes the overall driving conditions for each experiment. From the data recorded by the instrumented vehicle, plots were generated showing the speed of each participant's vehicle, and the displayed speed limit over the entire length of the VSL system. GPS data in conjunction with recorded speeds were used to plot the vehicle speed at various locations. The displayed speed limit was recorded by the researchers for each sign location, and is also displayed on the plots. This information gives a unique view of each participant's speed relative to the displayed speed limit. From these plots we can extract vital data regarding the interaction between the speed limit, the driver behavior, and the function of the VSL control algorithm. The analysis of the results showed that there were some specific types of scenarios which occurred with several drivers. A representative case of each scenario is presented in the remainder of this section. The plots for every driver can be found in Appendix C.

Several of the scenarios pertain to stretch of roadway near the SR-408 interchange. The geometry of the surrounding roadway is provided in Figure 3.4. Congestion typically forms first after the merge area from SR-408 WB, and backs up towards Kaley St.

The first type of scenario occurred when the driver's speed was reduced significantly near the SR-408 ramps, but the speed limit remained at its maximum value. An example of this is shown in Figure 3.5. In this case the speed limit remains high, despite congestion downstream. Near SR-408 the driver's speed drops well below 30 mph, but the displayed speed limit is still 50 mph. These conditions suggest that the VSL algorithm did not reduce the speed limit, either because of detector malfunction, or because the specific thresholds for speed limit reduction were not achieved.

Table 3.3 Driving experiment summary

Participant	Date	Start Time	End Time	Eastbound Comments	Westbound Comments
1	8/25/11	4:56 PM	5:27 PM	Speeds drop below 10 mph near SR-408, but speed limit is 40 mph.	Near SR-408, speed drops to 15 mph but speed limit is 50 mph
2	8/31/11	6:26 PM	6:48 PM	Through area near Princeton Street, the driver's speed is 70 mph and the speed limit is 40 mph	No congestion.
3	9/1/11	6:49 AM	7:17 AM	No congestion.	No congestion.
4	9/1/11	8:18 AM	8:49 AM	Speed change seems appropriate initially, but driver's speed is well below 30 mph and speed limit is 40 mph.	The driver's speed drops below 30 mph, but the displayed speed limit is 50 mph.
5	9/8/11	4:26 PM	4:58 PM	Near SR-408 the driver's speed drops below 10 mph, but the displayed speed limit is 50 mph.	Through the Fairbanks/Princeton area the driver's speed is approximately 70 mph, but the displayed speed limit is 40 mph. Once congestion starts around SR-408 the driver's speed is below 30 mph, but the speed limit is 50 mph.
6	10/5/11	5:01 PM	5:49 PM	Speed limit reduction seems to occur too far downstream. The driver's speed is reduced before reaching a reduced speed limit.	No congestion.
7	10/5/11	6:13 PM	6:57 PM	Erratic results due to an incident.	Speed limit reduction seems to occur too far downstream. The driver's speed is reduced before reaching a reduced speed limit.
8	10/6/11	8:26 AM	9:06 AM	Near Orange Blossom trail/408 the driver's speed drops below 30 mph, but the displayed speed limit is 40 mph.	Speed limit progression seems appropriate.
9	10/6/11	4:44 PM	5:30 PM	Near SR-408 the driver's speed drops below 30 mph, but the displayed speed limit is 40 mph.	Speed limit reduction seems to occur too far downstream. The driver's speed is reduced before reaching a reduced speed limit.
10	10/19/11	4:26 PM	5:00 PM	Near SR-408 the driver's speed drops below 30 mph but the displayed speed limit is 50 mph.	Near SR-408 the driver's speed drops below 30 mph, but the displayed speed limit is 50 mph.
11	10/19/11	6:13 PM	6:41 PM	Near SR-408 the driver's speed drops below 30 mph but the displayed speed limit is 50 mph.	No congestion.
12	10/20/11	6:57 PM	7:25 AM	Little to no congestion.	Little to no congestion.
13	10/20/11	7:56 AM	8:36 AM	From beginning of VSL zone the driver's speed well below 30 mph, but displayed speed limit is 50 mph.	Near SR-408 the driver's speed drops below 30 mph, but the displayed speed limit is 50 mph.
14	10/20/11	8:42 AM	9:20 AM	From beginning of VSL zone the driver's speed well below 30 mph, but displayed speed limit is 50 mph.	VSL control appears to be functioning properly (mild congestion)
15	10/26/11	4:14 PM	4:44 PM	Near SR-408 the driver's speed drops to 15 mph, while the displayed speed limit is 50 mph.	Brief drop in driver speed. No need for reduced speed limits.

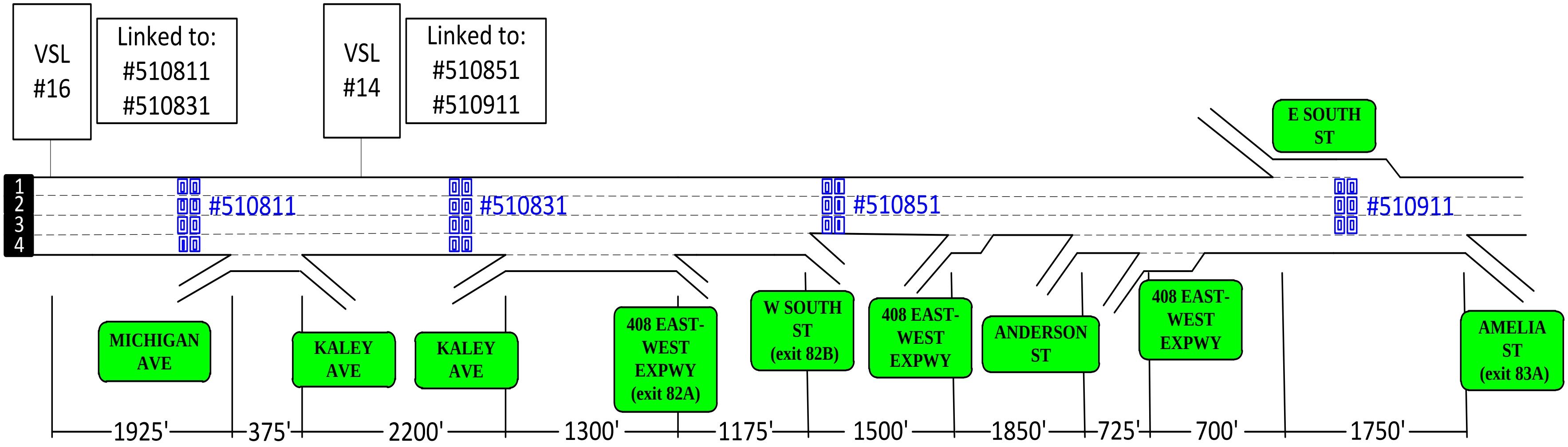


Figure 3.4 Location of detectors and VSL signs along I-4 eastbound near SR-408

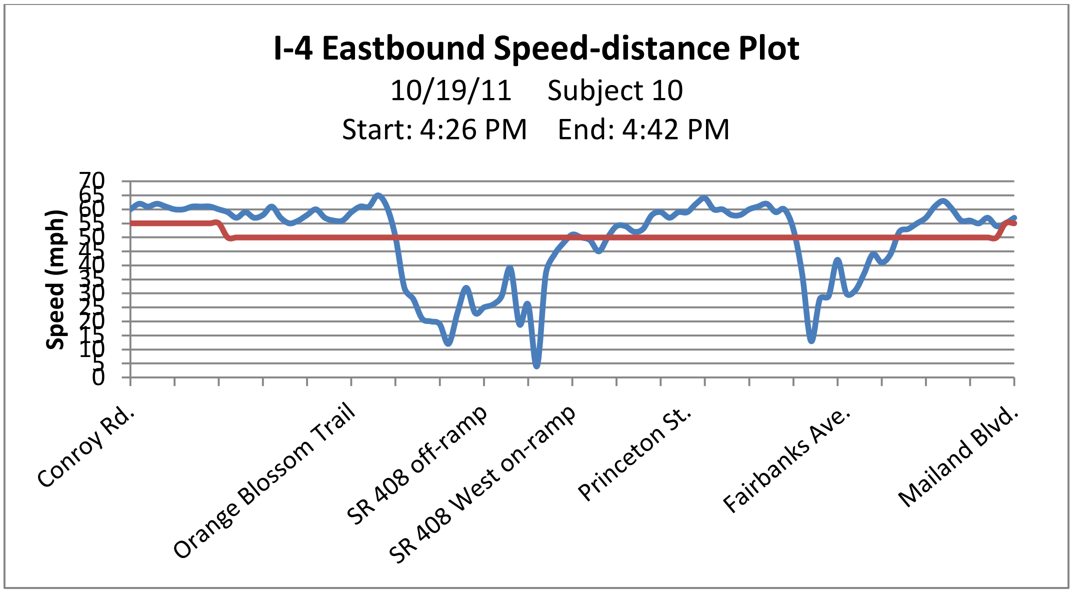


Figure 3.5 Speed versus distance with displayed speed limit

To gain a better understanding of the function of the VSL algorithm, the average occupancy and speed for 5-minute intervals were extracted from the STEWARD database for this day and time. The summary of this data is shown in Table 3.4.

Table 3.4 STEWARD data for 10/19/11 from 4:00 PM to 4:50 PM

	510811		**510831**			**510851**		**510911**		
Time	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**
16:00:00	8.6	48.8	21.3	34.5	15.0	8.6	48.8	21.3	34.5	15.0
16:05:00	8.1	53.5	19.4	36.0	13.8	8.1	53.5	19.4	36.0	13.8
16:10:00	7.9	53.2	16.4	43.7	12.2	7.9	53.2	16.4	43.7	12.2
16:15:00	8.3	53.2	10.6	54.2	9.5	8.3	53.2	10.6	54.2	9.5
16:20:00	8.2	53.4	10.8	56.3	9.5	8.2	53.4	10.8	56.3	9.5
16:25:00	9.5	50.3	17.4	43.9	13.5	9.5	50.3	17.4	43.9	13.5
16:30:00	7.3	54.3	25.6	27.8	16.5	7.3	54.3	25.6	27.8	16.5
16:35:00	7.0	55.3	22.2	30.3	14.6	7.0	55.3	22.2	30.3	14.6
16:40:00	10.6	43.3	26.5	26.2	18.6	10.6	43.3	26.5	26.2	18.6
16:45:00	8.6	44.8	26.8	25.0	17.7	8.6	44.8	26.8	25.0	17.7
16:50:00	8.7	53.1	23.9	35.6	16.3	8.7	53.1	23.9	35.6	16.3

The first sign, located just upstream from the Michigan St. entrance is linked to two detectors (510811 & 510831). The upstream detector location (510811) shows relatively high speeds and low occupancy values. The downstream detector location shows speeds as low as 30 mph and occupancy values as high as 27%. When these occupancy values are averaged, the threshold to decrease the speed limit to 40 mph is never reached. If the speed reduction were based solely on the downstream detector, a speed limit reduction would occur sooner.

The second sign is located just after the on-ramp from Kaley St. and is linked to detectors 510851 and 510911. From Table 3.4, the average occupancy relayed from the detectors should trigger a speed limit reduction around 4:30 PM, and not be increased back to 50 mph until 5:00 PM. However, the speed was not reduced during the driving experiment. A closer look at the occupancy values associated with detector 510911 suggests that this specific detector may not be calibrated properly. The occupancy values appear to be too low for the given speed conditions.

The second type of scenario occurs where the speed limit is reduced to 40 mph near the SR-408 ramps, but the traffic conditions suggest the speed be reduced further to 30 mph. An example of this scenario is shown in Figure 3.6.

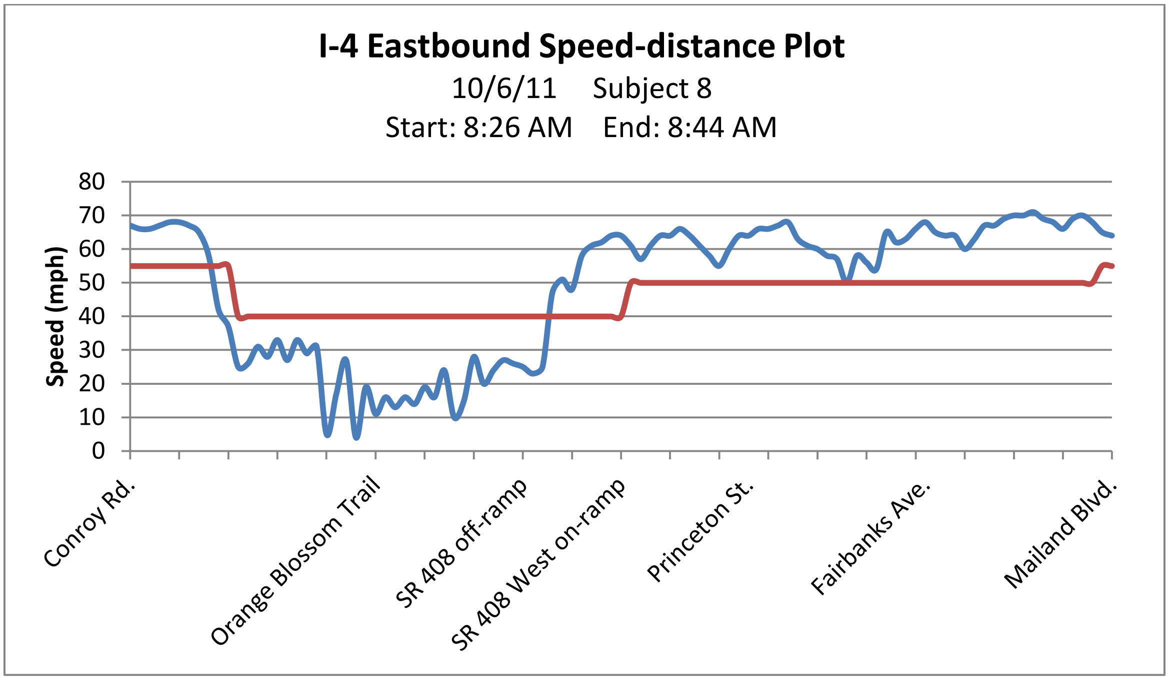


Figure 3.6 Speed versus distance with displayed speed limit

From the figure it is apparent that the driver's speed drops well below 30 mph at the beginning of the VSL zone, however the displayed speed limit is 40 mph. It should be noted that only once during the entire experiment did the displayed speed limit drop to 30 mph, and this was while an incident was being cleared from the interstate. The STEWARD data for average speed and occupancy associated with this day and time are shown in Table 3.5.

Table 3.5 STEWARD data for 10/6/11 from 8:00 AM to 8:50 AM

	510811		**510831**			**510851**		**510911**		
Time	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**
8:00:00	17.1	30.7	32.5	21.8	24.8	31.9	14.7	18.2	23.0	25.1
8:05:00	21.8	23.8	29.8	23.4	25.8	35.2	13.2	14.5	30.4	24.9
8:10:00	24.1	18.5	32.8	19.1	28.5	34.4	12.1	15.1	32.5	24.8
8:15:00	21.2	20.1	26.7	25.4	24.0	32.4	15.1	18.3	23.1	25.4
8:20:00	23.5	20.0	26.9	26.9	25.2	38.0	9.9	17.1	27.4	27.6
8:25:00	25.6	17.4	30.9	22.6	28.3	33.8	12.3	17.9	24.5	25.9
8:30:00	21.8	20.8	28.6	23.6	25.2	36.9	12.9	16.3	27.7	26.6
8:35:00	24.7	19.3	31.3	24.2	28.0	36.6	9.4	15.9	29.8	26.3
8:40:00	22.7	20.0	32.5	21.0	27.6	38.7	9.1	16.6	28.3	27.7
8:45:00	23.2	19.1	33.7	21.5	28.5	34.6	11.6	17.6	25.1	26.1
8:50:00	23.7	18.3	32.6	20.2	28.2	36.1	12.6	18.6	25.1	27.4

As shown in Figure 3.6, in this case the upstream detector location (510811) shows speeds at or below 20 mph, however the occupancy values range from 22% to 25% which is consistent with a speed limit of 40 mph according to the control thresholds. The downstream detector location shows speeds ranging from 21 mph to 27 mph, and occupancy values ranging from 27% to 34%. When these occupancy values are averaged, the threshold to decrease the speed limit to 30 mph is not reached. However, the threshold would have been reached if the speed limit reduction were based solely on the downstream detector.

The second sign is located just after the on-ramp from Kaley St., and is linked to detectors 510851 and 510911. From Table 3-5, the average occupancy relayed from the upstream detector (510851) ranges from 34% to 39 %, which is well above the threshold to reduce the speed limit to 30 mph. The downstream detector (510911) displays much lower occupancy values ranging from 16% to 18%, while the speeds range from 25 mph to 30 mph. Again, when these two detectors are averaged the resulting occupancy is below the threshold to reduce the speed limit to 30 mph. If only the upstream detector is used, the speed limit would have been reduced to 30 mph. Detector 510911 again appears to relaying occupancy values well below expected occupancy percentages given speed conditions.

The third observed type of scenario occurs when the speed limit is reduced, but the driver's speed is well above the speed limit. A speed distance example of this scenario is shown in Figure 3.7, and the geometry of the surrounding roadway is shown in Figure 3.8.

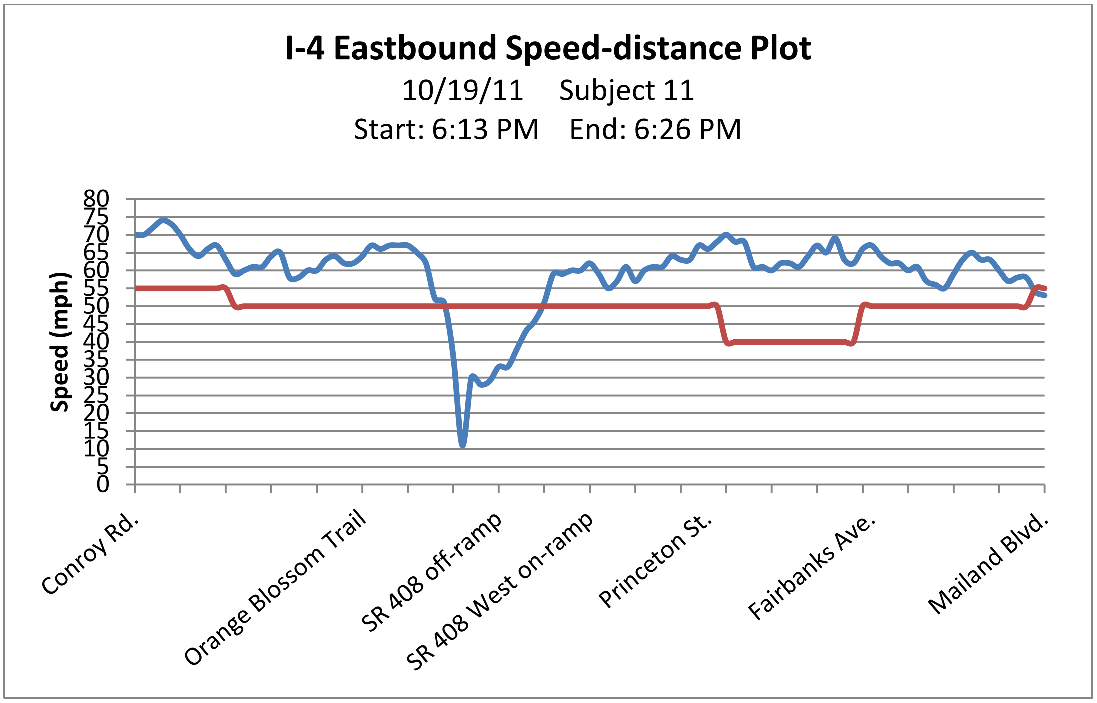


Figure 3.7 Speed versus distance with displayed speed limit

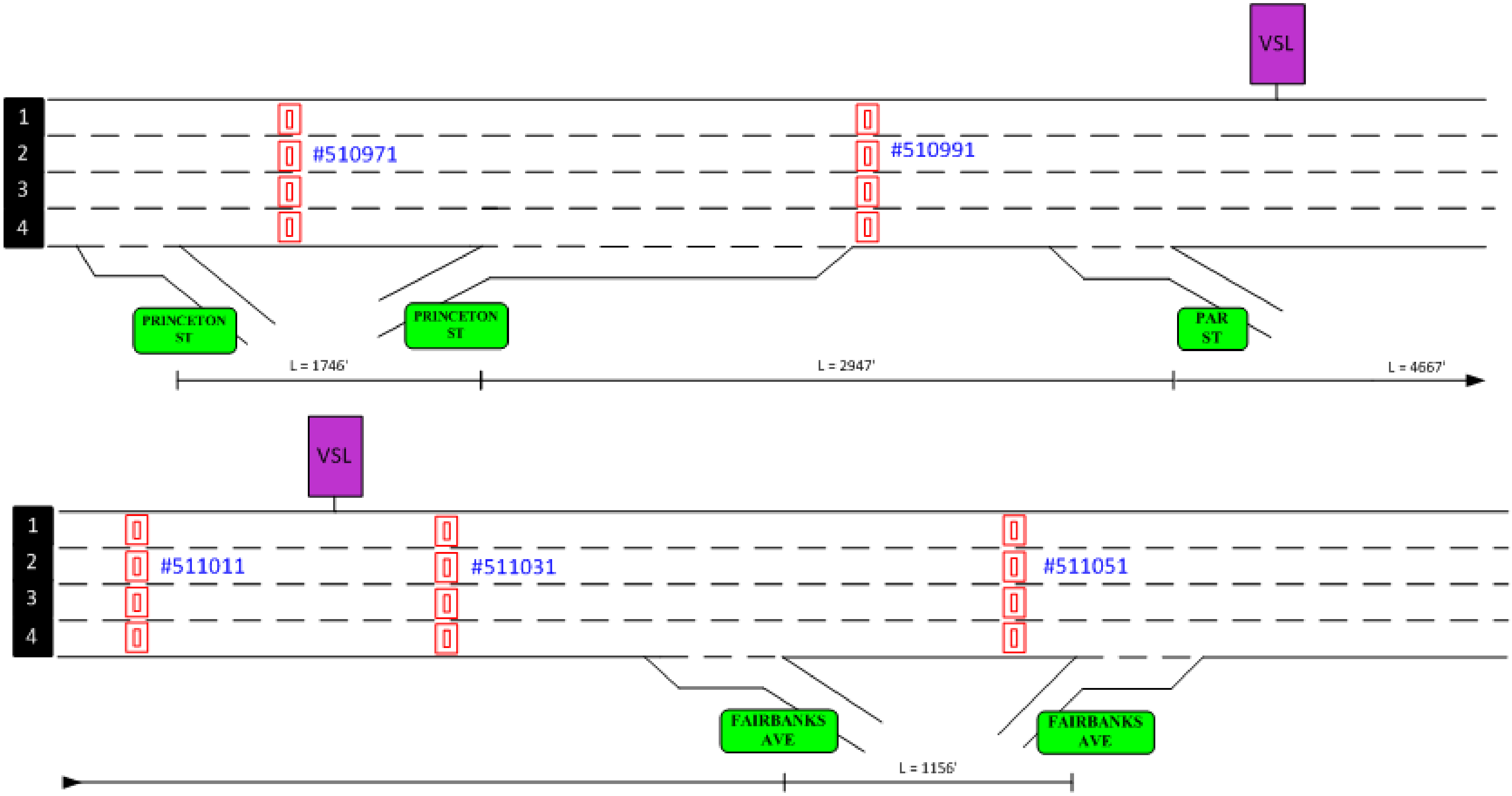


Figure 3.8 Location of detectors and VSL signs along I-4 eastbound near Fairbanks Ave

In this case it appears the traffic conditions are at free flow speed near Fairbanks Ave, but a reduced speed limit is displayed. The corresponding STEWARD data for this time and date are shown in Table 3.6.

Table 3.6 STEWARD data for 10/19/11 from 6:00 PM to 7:00 PM

	510991		**511011**		
Time	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg. Occ. (%)**
18:00:00	9.7	57.3	9.7	56.3	9.7
18:05:00	8.9	59.2	8.7	59.7	8.8
18:10:00	8.9	60.9	9.0	59.3	9.0
18:15:00	8.8	60.0	8.5	62.0	8.7
18:20:00	8.5	60.5	9.1	60.3	8.8
18:25:00	8.6	61.5	8.3	62.5	8.5
18:30:00	7.6	62.6	7.5	61.2	7.6
18:35:00	7.3	62.8	7.6	59.2	7.5
18:40:00	7.4	60.9	8.0	60.1	7.7
18:45:00	8.1	60.4	7.9	59.8	8.0
18:50:00	8.0	61.0	8.8	57.5	8.4
18:55:00	8.0	61.2	7.7	58.8	7.9
19:00:00	6.8	62.7	7.1	58.2	7.0

The VSL sign located directly after Princeton St. is linked to detectors 510911 and 511011. The average occupancy values relayed by both these detectors are below 12%. At this occupancy level the speed limit should be at the maximum value of 50 mph. It is possible that the area has experienced congestion previously, and the new speed limit has not been implemented yet.

The fourth and last type of scenario observed relates to the location and utilization of the detectors. The geometry of the area, including VSL signs and associated detectors are shown n Figure 3.9. Congestion typically occurs starting just downstream from detector 510891 just after the SR-408 WB on-ramp, and propagates upstream towards Kaley St. This congestion also propagates downstream ending after the exit to Amelia St. There were several instances where the driver’s speed dropped significantly at this location, but the speed limit was not reduced until farther downstream. The speed distance plot corresponding to this scenario is shown in Figure 3.10.

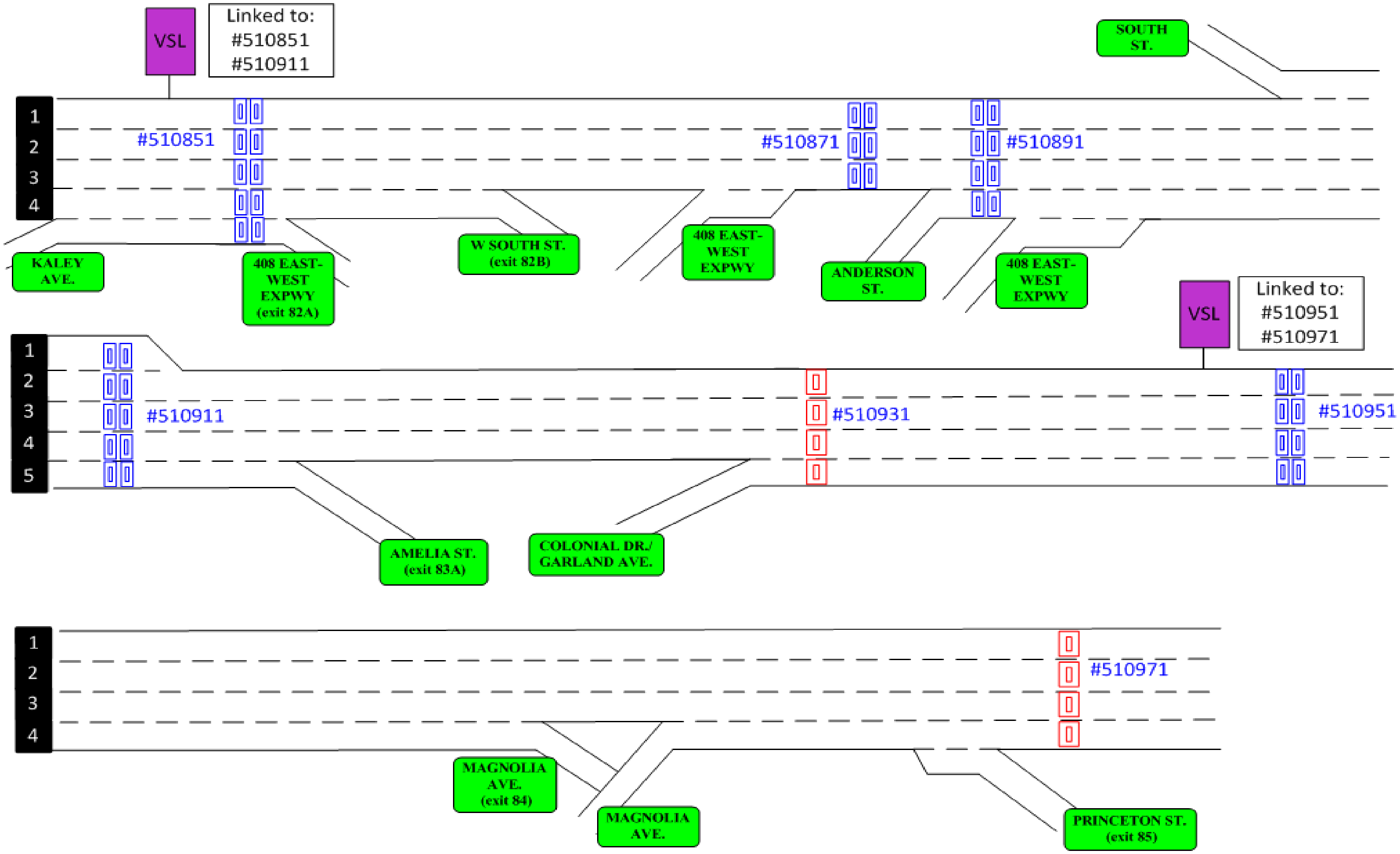


Figure 3.9 Location of detectors and VSL signs along I-4 eastbound near Colonial

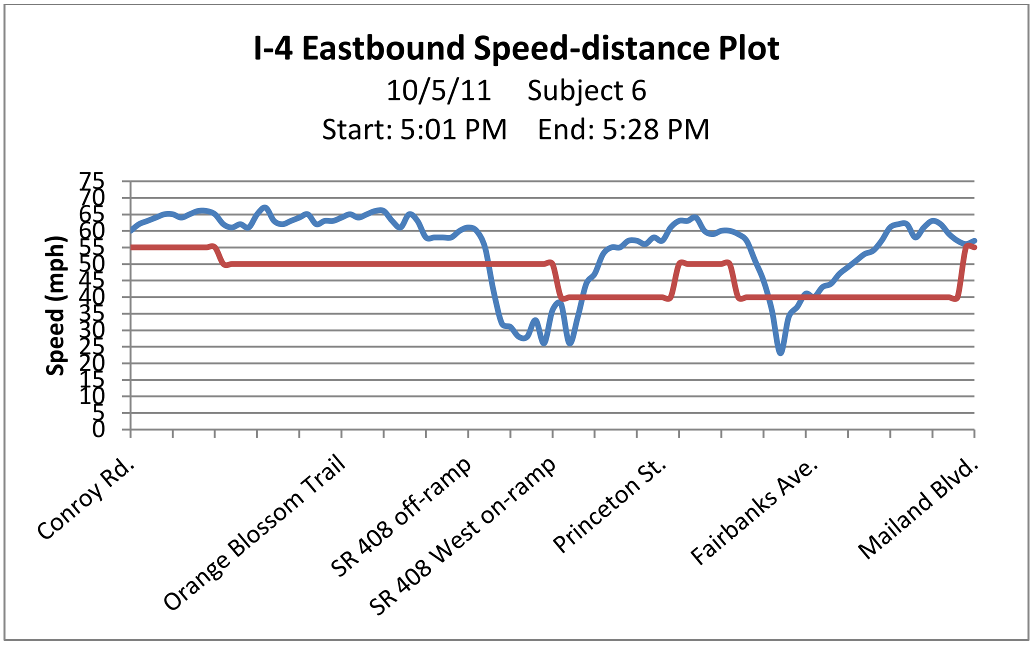


Figure 3.10 Speed versus distance with displayed speed limit

Figure 3.10 shows that the driver's speed drops well in advance of the reduced speed limit sign. The corresponding STEWARD data for this time and day are shown in Table 3.7.

Table 3.7 STEWARD data for 10/5/11 from 4:30 PM to 5:30 PM

	510851		**510911**			**510951**		**510971**		
Time	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**	**Occ. (%)**	**Speed (mph)**	**Occ. (%)**	**Speed (mph)**	**Avg Occ. (%)**
16:30:00	38.0	10.3	18.0	22.9	28.0	18.8	43.4	13.3	60.6	16.1
16:35:00	32.1	17.3	16.6	23.8	24.4	18.2	43.3	13.8	58.1	16.0
16:40:00	32.8	14.6	16.8	26.0	24.8	19.8	40.3	12.8	60.5	16.3
16:45:00	32.7	12.7	20.3	20.9	26.5	20.0	40.7	13.3	59.0	16.7
16:50:00	36.5	13.3	14.4	28.9	25.5	19.3	43.2	13.6	59.6	16.5
16:55:00	24.7	21.7	15.2	27.2	20.0	18.9	43.5	13.7	60.1	16.3
17:00:00	30.1	16.8	18.0	21.3	24.1	16.9	43.7	14.9	51.5	15.9
17:05:00	32.6	14.6	19.0	19.0	25.8	18.5	41.3	13.4	52.9	16.0
17:10:00	39.2	10.9	16.1	23.1	27.7	24.3	34.1	29.6	28.3	27.0
17:15:00	31.2	12.9	19.7	21.8	25.5	21.1	36.9	35.9	24.6	28.5
17:20:00	36.5	12.1	17.5	23.4	27.0	29.1	25.6	32.3	26.3	30.7
17:25:00	31.0	11.8	21.1	17.5	26.1	21.5	34.7	32.8	27.2	27.2
17:30:00	36.9	8.7	16.9	24.0	26.9	21.8	37.9	25.6	33.0	23.7

For this type of scenario, two different VSL signs are of interest. The first sign is located just after the on-ramp from Kaley St, and is linked to detectors 510851 and 510911. During the driving experiment, this sign displayed a speed limit of 50 mph. From Table 3.7, the average occupancy relayed from the upstream detector (510851) ranges from 30% to 39 %, which is well above the threshold to reduce the speed limit to 30 mph. The downstream detector (510911) displays much lower occupancy values ranging from 18% to 21%, while the speeds range from 17 mph to 24 mph. Based on the average of these two detectors, the displayed speed limit should be 40 mph. If only the upstream detector is used, the speed limit would have been reduced to 30 mph. Detector 510911 again appears to relaying occupancy values well below expected occupancy percentages given the speed conditions.

The second VSL sign of interest is located just downstream from the Colonial Dr. on-ramp. This sign is linked to detectors 510951 and 510971. During the driving experiment this sign displayed a speed limit of 40 mph. From the STEWARD data for the given time period, this displayed speed is appropriate. The issue with this scenario was that the appropriate speed was not implemented at the first VSL sign (downstream from Kaley St.). According to the STEWARD data, a 40 mph speed limit should have been implemented at least an hour prior to the driving experiment.

3.3.1 Summary of Speed Distance Plots

From the analysis of the speed-distance plots, several potential issues have been raised. First, there are cases when that the displayed speed limit is too high for the driving conditions. These cases apply to two different VSL signs. The first sign is located downstream from the Orange Blossom Trail on-ramp. The two detectors associated with this sign show vastly different occupancy readings. The upstream detector (510811) typically relays lower occupancy values than the downstream detector (510831). When averaging the two detector readings, the higher value is diluted and an occupancy threshold is never reached. If the VSL sign were linked only to the downstream detector or to the maximum reading from the two detectors, the displayed speed would more appropriately control the speed of traffic.

The second sign is located downstream from the on-ramp from Kaley St. This sign is linked to two different detectors (510851 & 510911). In this case the downstream detector (510911) will typically reach the occupancy threshold to reduce the speed limit to 40 mph first. However, the upstream detector (510851) will reach the occupancy threshold to reduce the speed limit to 30 mph, while the downstream detector will never reach this threshold. Again, one possible solution would be to take the maximum occupancy of the two detectors.

The second major issue identified is the reliability of detector 510911. The occupancy values relayed by this detector do not seem appropriate at lower speed conditions. Chapter 6 discusses VSL-detector associations in more detail, when testing various alternative VSL scenarios.

3.4 Results of the Post-Driving Questionnaire

After each participant completed the route, he/she filled out a questionnaire that asked about their driving speed relative to the speed limit, their knowledge, and perception of the VSL system. Thirteen out of fifteen participants indicated that their speed selection is primarily based upon the surrounding flow of traffic, rather than the posted speed limit. While driving, some participants stated what the posted speed limit was and then proceeded to explain that they would not feel safe if they attempted to travel at that speed. When asked what improvements could be made to the VSL system, six participants were recorded as stating that the speed limit should be higher than 50 mph. Four participants stated that, without increased law enforcement, the signs will continue to be largely ignored. Drivers were also asked about the visibility of the speed limit signs. There was no consensus about how visible the signs are. Eight participants said the signs were currently visible. Seven participants said the signs were difficult to see at times, and it would be better if there was an overhead sign or signs on either side of the freeway. Overall, based upon observations made during the driving experiment and responses by the participants, it appears that the flow of traffic is the dominating factor in individuals’ speed selection, and unless there is increased enforcement, this will continue to be the case.

3.5 Summary

A total of 15 participants were recruited to perform the in-vehicle driving experiment. Based on the results from the instrumented vehicle several observations can be made about the current operation of the VSL signs.

Based on the speed versus distance plots, several potential issues were identified. Near the SR-408 area, the displayed speed limit is often higher than the prevailing conditions. Adjusting threshold values or changing the VSL sign/detector association are potential ways to address this discrepancy. Chapter 6 provides additional suggestions regarding modifications to these associations.

Another problem identified was the accuracy of detector 510911. It appeared that the occupancy values being relayed by this detector were too low for the prevailing speeds.

The responses of drivers to the post-driving questionnaire were in agreement with the results of Chapter 2. For the most part, drivers base their speed on the flow and traffic, and are minimally affected by the variable speed limit signs. Increased enforcement of speed limits may be the only means of driver compliance with the speed limits. The visibility of the signs may be an issue. Larger more visible signs, or signs on either side of the road may help drivers recognize the displayed speed limit.

4 I-4 VSL ZONE ASSESMENT AND BOTTLENECK IDENTIFICATION

4.1 Introduction

The objective of the I-4 VSL zone assessment and bottleneck identification was to use the I-4 corridor sensors' speed and flow traffic data and identify the bottleneck locations on both the eastbound and westbound directions. The time of day when the bottlenecks appear to be activated were also determined. The following sections discuss the traffic data obtained for the detectors located along the I-4 corridor, and provide the analysis results along with a list of all bottlenecks along the I-4 corridor.

4.2 Data

For the VSL zone assessment and identification of the bottleneck locations, the traffic data collected by the ITS detectors (maintained by FDOT's SunGuide system software) located along the I-4 VSL zone for both westbound and eastbound were used. The raw traffic data for these detectors were obtained from the Florida's Central Data Warehouse, STEWARD (Statewide Transportation Engineering Warehouse for Archived Regional Data) system at the University of Florida.

Fifty four detectors along the I-4 corridor between the interchanges of Conroy Road and Lake Mary Boulevard were identified as the sites of interest for this task. The raw data for these detectors were obtained from the STEWARD database, and were processed into an aggregated data format. To aggregate the data, the research team prepared a facility file that included information on the detector locations, detector descriptions, lane-mapping configurations, mile-posts, speed limits, and etc. An ETL (Extraction Transformation Loading) utility (provided by STEWARD) was used to process the raw data into 1-, 5-, 15- and 60-minutes aggregated data. To meet the purpose of this study, traffic data from August 2010 through May 2011 were processed and used for the analyses. To ensure the quality of the data, the research team worked with the STEWARD database operators to obtain the best possible data available for these months.

4.3 Data Analysis

To examine the bottleneck locations along the I-4 corridor, the research team explored the most appropriate methodology to achieve the objective of this task. Given the acceptance and advantages that the traffic breakdown analysis has provided in most recent freeway facility research, the analyses to identify bottlenecks were primarily based on determining the breakdown events along the I-4 corridor. As the motive was to determine locations that are either the source of recurrent congestion or the locations that triggers congestion on a facility, an analysis dependent on breakdown events was expected to provide the most accurate results.

To identify the breakdown events, the approach suggested by Washburn et al. (2010) was used. According to the authors, the breakdown events are typically identified by looking at sudden changes in traffic flow measurements or relationships, such as speed, occupancy, and correlation between volume and occupancy. The authors suggested the use of sudden changes in speed values to identify traffic breakdown events. This means that whenever the average speed drops below a particular speed value (i.e., a speed threshold value) for a specific period of time, a breakdown event is considered to have occurred. Further, it was also suggested that “true” breakdown events should be considered for the data analyses. The “true” breakdown events as referred by the authors relate to congested conditions that are not a result of downstream congestion propagating upstream to the freeway segment under study. This meant that once a breakdown event was identified at a particular location, the downstream conditions were also evaluated to make sure there was a not a queue propagating upstream from a downstream bottleneck at the same time. The authors further added that with the help of the speed threshold values, the breakdown events and the respective breakdown times could be determined. A breakdown event as determined from this approach was reported as the beginning and end of congestion times for a freeway segment. Given the sound theoretical concept of this approach, the research team decided to use the mechanism of breakdown events to identify the bottleneck locations.

To use the approach as suggested by Washburn et al. (2010), the speed threshold values for the detectors located along the I-4 corridor were determined. To determine the speed threshold values for the detectors, the speed time-series plots, where section average speeds (i.e., the volume-weighted average speeds) were plotted in one-minute time intervals for a period of one month (November 2010). The speed threshold values for each detector location was then determined by visually observing the speed drop for a period of 5- or more minutes at each location. Next, to identify the start and end times of a breakdown event, a utility program, called Capacity Data Processor (CDP), provided by Washburn et al. (2010), was used. The inputs for running the CDP utility were: 1-minute volume and speed traffic data, the analysis time period (considered from 5 AM - 10 PM); the speed threshold value (as determined earlier for each detector location) and, the recovery time for a breakdown event (5-minutes; i.e., a breakdown event is recovered when the section average speed goes above the speed threshold value for at least 5-minutes). To eliminate the breakdown events that occurred because of downstream congestion, another utility program, called Downstream Breakdown Identifier (DBI) by Washburn et al. (2010), was used. The end result after using the DBI utility was the number of breakdown events at a particular detector location along with the start and end times of the respective breakdown events.

Using the number of breakdown events and the respective start/end times, the bottleneck analyses were performed. The following section describes the analyses performed in this study. At first, a preliminary analysis was done by using the bottleneck analysis methodology, and from the results of this analysis, an expanded approach with additional data was suggested and applied.

4.3.1 Preliminary Analysis

The first approach in identifying the bottlenecks was to compute the average number of breakdown events per day at selected detector locations from the traffic data obtained from the STEWARD database. The motivation was to identify locations that experience the highest average number of breakdown events per day along the I-4 corridor and to assign the location as the bottleneck location. The breakdown analysis as described in Section 4.3 was used to identify the breakdown events and the respective breakdown times.

For this approach, a detector in close proximity of each interchange between Conroy Road and Maitland Boulevard were selected covering the entire stretch of I-4 with active VSL system. To start with, only 38 days of data from the months of September 2010 and November 2010 were used in this approach. The 1-minute volume and speed data were obtained for the selected detector locations and the utilities as provided by Washburn et al. (2010), CDP and DBI, were run to obtain the details on the breakdown events at the respective detector locations. The total number of breakdown events at each selected detector location for 38 days including the average breakdown events per day was computed. Table 4.1 lists the results from this approach that includes the details on the breakdown events, total breakdown events and the average breakdown events per day. The breakdown times that appeared frequently at each detector location are also provided in Table 4.1.

From the results of this approach, the detector locations with the highest average number of breakdowns were identified as the bottleneck locations on I-4. For example, detector locations with ID's '511242' (west of Altamonte Springs) and '510902' (at South Street) in the westbound direction were found to be the most congested and hence were identified as bottleneck locations. Similarly, detector locations with ID's '510751' (East of John Young Parkway) and '510781' (West of Orange Blossom Trail) in the eastbound direction were found to be most congested, and were identified as bottleneck locations.

Though it was a good start to identify the bottleneck locations based on the breakdown events, the high uncertainty in the selection of the detector locations remained a concern as the origin of the traffic congestion was not explored. Also, the question on exactly where the onset of congestion gets triggered remained unanswered. Therefore, it was decided that a more detailed analysis was required that could provide more insight on the bottleneck locations and not merely the locations that experience the highest number of breakdown events per day. To address this, an expanded approach was discussed which is described next in Section 4.3.2.

Table 4.1 Preliminary analysis in identifying the breakdown locations along I-4 corridor

Detector ID	Detector Location	Lanes	No. of breakdowns	Avg. breakdowns/ day	Frequent breakdown periods		Bottleneck Type
					AM period	PM period	
I-4 WESTBOUND							
510772	I-4 West of SR-441	4	52	1.37	-	15:30-15:45, 17:00-17:15	On-Ramp Merge
510802	I-4 At SR 441/OBT	4	21	0.55	-	15:45-16:00, 17:15-17:30	Off-Ramp/On-Ramp Merge
510902	I-4 At South Street	4	102	2.68	7:45-8:00	15:15-15:30, 16:45-17:00	On-Ramp Merge
510922	I-4 At Robinson Avenue	4	87	2.29	7:45-8:00, 8:15-8:30	16:15-16:30, 17:15-17:30	On-Ramp Merge
510942	I-4 At SR-50	3	75	1.97	7:45-8:00	16:45-17:00, 17:15-17:30	On-Ramp Merge
510962	I-4 At Ivanhoe Boulevard	3	82	2.16	7:45-8:00	15:45-16:00, 17:15-17:30	On-Ramp Merge
511022	I-4 At Par Avenue	4	74	1.95	7:45-8:00	16:45-17:00, 17:15-17:30	On-Ramp Merge
511142	I-4 At Kennedy Boulevard	4	96	2.53	7:15-7:30, 7:30-7:45	14:45-15:00, 15:45-16:00	On-Ramp Merge
511242	I-4 West of SR-436	4	128	3.37	7:00-7:15, 7:15-7:30	13:45-14:00	On-Ramp Merge
I-4 EASTBOUND							
510751	I-4 East of John Young Parkway	4	138	3.63	7:15-7:30, 8:45-9:00	16:45-17:00, 17:30-17:45	Off-Ramp Diverge
510781	I-4 West of SR-441/OBT	4	127	3.34	7:30-7:45, 7:45-8:00	16:45-17:00, 17:15-17:30	Off-Ramp Diverge
510851	I-4 West of SR-408	3	117	3.08	7:30-7:45	16:00-16:15, 16:45-17:00	Off-Ramp Diverge
510871	I-4 At SR-408	3	112	2.95	7:30-7:45	15:30-15:45, 16:00-16:15	Lane Drop
510991	I-4 West of Par Avenue	4	62	1.63	-	15:45-16:00, 17:15-17:30	On-Ramp Merge
511011	I-4 At Par Avenue	4	70	1.84	-	15:45-16:00, 17:00-17:15	On-Ramp merge
511111	I-4 East of Lee Road	4	83	2.18	-	16:45-17:00, 17:00-17:15	On-Ramp Merge

4.3.2 Expanded Approach

Given the uncertainty in the selection of detectors and the origin of the congestion along the I-4 corridor, an expanded approach was proposed. In this approach, the breakdown events and the respective breakdown times at consecutive detector locations along the I-4 corridor were determined, and the detector location where congestion is most likely to occur first was determined and considered as the bottleneck location. To select the detector locations for the analyses, the observations from the 'trial' flight of the aerial reconnaissance task were examined. The observations indicated that the congestion along the westbound direction occurs mostly outside the existing VSL zone. Therefore, the limits of the I-4 westbound corridor were extended on the eastern side from Maitland Boulevard to Lake Mary Boulevard. All the detectors between Maitland Boulevard and Lake Mary Boulevard were also considered for the analyses in the expanded approach. At the same time, the detectors considered in the eastbound direction remained between the limits of Conroy Road and Maitland Boulevard.

From the results of the first approach where the average highest number of breakdown events per day were determined, it was decided that the comparisons of breakdown times would be performed for all detectors that lie in close proximity of major interchanges. The criteria to select the interchanges were: the interchange experiences a high number of breakdown events per day and it is not spaced within two miles of another interchange. The motivation behind the selection of interchanges was to limit the regions where the comparisons of breakdown times would be performed. The interchanges were further classified into zones, with several detectors located in each zone. As a result, the I-4 corridor was divided into zones between Conroy Road and Lake Mary Boulevard along the westbound direction, and into zones between Conroy Road and Maitland Boulevard along the eastbound direction.

Five zones, W1, W2, W3, W4, and W5, were created along the westbound direction, containing the detectors within the close proximity of interchanges at Lake Mary Boulevard, Altamonte Springs, Maitland Boulevard, Fairbanks Avenue, and East-West Expressway, respectively. Similarly, four zones, E1, E2, E3, and E4, were created along the eastbound direction, containing the detectors within the close proximity of Maitland Boulevard, Fairbanks Avenue, East-West Expressway, and Orange Blossom Trail, respectively. The list of all zones that contain the detectors within respective interchanges is provided in Table 4.2. These zones are also marked on a Google map in Figures 4.1 and 4.2 for westbound and eastbound directions, respectively.

Table 4.2 VSL zones along I-4 corridor with the respective major interchange

I-4 Westbound Zones	**I-4 Interchange**	**I-4 Eastbound Zones**	**I-4 Interchange**
W1	Lake Mary Boulevard	E1	Maitland Boulevard
W2	Altamonte Springs (SR-436)	E2	Fairbanks Avenue
W3	Maitland Boulevard	E3	East-West Expressway (SR-408)
W4	Fairbanks Avenue	E4	Orange Blossom Trail
W5	East-West Expressway (SR-408)		

After the zones were created, the speed threshold values for all the detectors in the selected zones were determined. The speed threshold value, along with the 1-minute volume and speed data, were used in the utilities CDP and DBI, as described in Section 4.3, to determine the breakdown events and breakdown times at each detector location. Next, the breakdown times at each detector location within a zone were compared to each other, and the detector location where a breakdown event appears to occur first was identified. The detector location that appeared first was then considered as the bottleneck location in that respective zone.

A sample comparison of the breakdown times from one zone along westbound and eastbound directions are provided in Appendix D. For example in Table D.1, the comparisons for the zone ‘W1’ are explained in detail. In this table, the breakdown times for all the detectors inside the zone are listed for the morning period. The breakdown times for this set of comparisons are provided for some randomly selected days from the months of November 2010, January 2011 and April 2011. The detector location with ID ‘511482’ (West of Lake Mary) appears to get congested first and is considered as the trigger point to cause congestion in the zone. The breakdown times associated with the detector location are highlighted in gray in the table. This detector is located just downstream of the on-ramp from Lake Mary Boulevard onto I-4 westbound direction and within close proximity of a lane-drop on I-4. Therefore, this detector location could be considered as a bottleneck location along I-4 westbound. To illustrate the consistency of the results obtained from the comparisons, the results from three random days across the three selected months are tabulated in Table D.1.

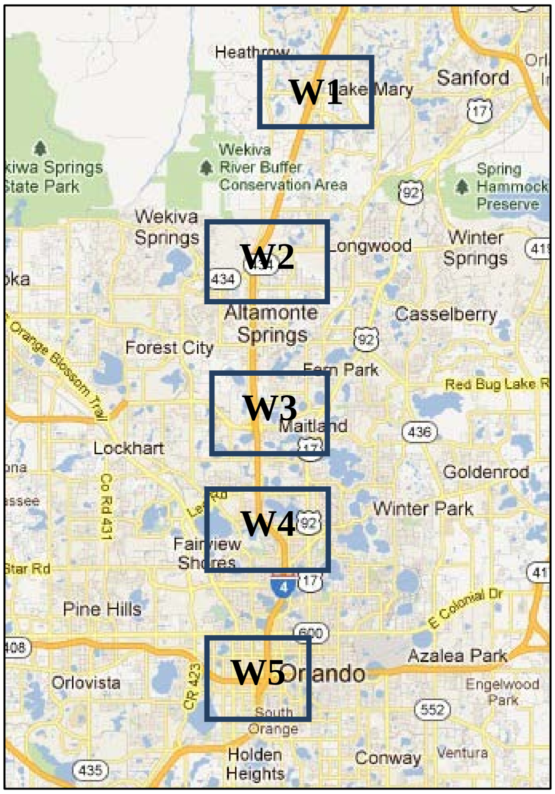


Figure 4.1 Google Map displaying zones along I-4 westbound direction

Figure 4.2 Google Map displaying zones along I-4 eastbound direction

Similarly, an example from the zones E3 and E4 is also explained in Table A4.2. In Table A4.2, the detector location with ID 510911 (at Robinson Avenue) appears to get congested before other detectors in close proximity get congested, and the corresponding breakdown times are highlighted in the table. At the same time, the detector location with ID 510891 (at South Street) also appears to have similar breakdown times with detector ID 510911, indicating that the facility at this location has a bottleneck. This section of the facility is located between the on-ramp from East-West Expressway (SR-408) and the off-ramp to Amelia Street. The weaving movement between the on-/off-ramps could be considered as the source of congestion in this zone. It should be also noted that there is no true bottleneck in zone E4, as the breakdown times are merely the result of downstream congestion in zone E3.

For all the zones, the breakdown times at each detector location inside a zone were compared with each other, and the source of the congestion was identified. The summary of the analyses and the major findings from the comparisons that indicate the respective bottleneck location in all the zones are provided in Tables 4.3 and 4.4 for both westbound and eastbound directions, respectively. All the identified bottlenecks were studied and reviewed with the help of the video recordings from the aerial reconnaissance task of this project. The observations from the aerial recordings at a given time of the day supported the results obtained from the bottleneck identification analysis. These findings were then presented to FDOT project management during a teleconference call held on 15th August 2011. The aerial video clips showing the operations of the bottleneck locations were also shared with FDOT.

The snapshots of the bottleneck locations as confirmed from the aerial reconnaissance task are provided in Chapter 5 of this report. The factors that influence the congestion at the respective bottleneck locations are also described in detail in Chapter 5.

Table 4.3 Summary of the comparisons of breakdown times for all the westbound zones

I-4 WB Zone	**Breakdown Times**	**Bottleneck (Type)**	**Bottleneck Description**
W1 (Lake Mary Boulevard	AM: 6:50 - 7:10 AM PM: None	On-ramp from Lake Mary Boulevard (lane drop)	• Detector location at the downstream of the on-ramp from Lake Mary Boulevard was found to be the source of congestion in the morning hours. The lane drop could possibly attribute to the congestion along I-4 WB.
W2 (Altamonte Springs)	AM: 7:15 AM PM: None	On-ramp from SR-436 (lane drop)	• Detector location at the downstream of the on-ramp from Altamonte Springs (SR-436) was found to be the source of congestion in the morning hours. The lane drop could possibly attribute to the congestion along I-4 WB. Similar results were also observed at the SR-434 interchange.
W3 (Maitland Boulevard)	AM: 7:30 – 8:00 AM PM: None	On-ramp from Maitland Boulevard* (merge operations)	• Detector location at the downstream of the on-ramp from Maitland Boulevard was found to be the source of congestion in the morning hours.
W4 (Fairbanks Avenue)	AM: None PM: 5:00 – 5:30 PM	On-ramp from Fairbanks Avenue* (merge operations)	• None of the detector locations were found to be congested in the morning hours. • The detector location at downstream of on-ramp from Lee Road appeared to be a potential bottleneck. The bottleneck could be a result of horizontal terrain or the high on-ramp demand.
W5 (SR-408)	AM: None PM: 3:00 – 5:00 PM	Off-ramp to SR-408 (diverge operations)	• The high demand for the off-ramp to SR-408 is found to be the source of recurrent congestion in this zone. This was also found to congest the upstream locations on WB direction till Ivanhoe Boulevard.

*potential bottlenecks

Table 4.4 Summary of the comparisons of breakdown times for all the eastbound zones

I-4 EB Zone	**Breakdown Times**	**Bottleneck (Type)**	**Bottleneck Description**
E1 (Maitland Boulevard)	AM: None PM: 4:00– 5:30 PM	On-ramp from Maitland Boulevard (merge operations)	- Congestion did not appear in the morning hours - Detector location downstream of on-ramps from WB and EB Maitland Boulevard appears to be the source of congestion. The high demand from on-ramps could attribute to this observation.
E2 (Fairbanks Avenue)	AM: None PM: 4:30 – 5:00 PM	On-ramp from Fairbanks Avenue (merge operations)	- Congestion did not appear in the morning hours - Detector location downstream of on-ramp from Fairbanks Avenue on I-4 appears to be the source of congestion. The high demand from the on-ramps and the horizontal terrain at this location could attribute to this observation.
E3 (SR-408)	AM: 7:15 – 7:30 AM PM: 3:30 – 6:00 PM	On-ramp from SR-408 and off-ramp to Amelia Street (merge operations) Off-ramp to SR-408 (diverge operations)	- The location where the entrance ramp from WB SR-408 merges with I-4 EB was found to be a major bottleneck. The high demand for the off-ramp towards Amelia Street was also found to be another source of congestion. - During the afternoon hours, the off-ramp to SR-408 from I-4 EB was found to be congested for most of the analysis period due to high demand on this single lane ramp. The congestion on this ramp also causes lengthy queues on the auxiliary lane and extends onto I-4 mainline
E4 (OBT)	AM: None PM: None	Off-ramp to Kaley* (diverge operations)	- No source of congestion was found at this location during the morning and evening hours; the congestion occurred primarily due to downstream congestion at zone E3.

*potential bottleneck

4.4 Summary and Conclusions

To identify the bottleneck locations along the I-4 corridor, breakdown analysis was performed for detectors installed on I-4. The corridor was divided into five zones between Conroy Road and Lake Mary Boulevard in the westbound direction and four zones between Conroy Road and Maitland Boulevard in the eastbound direction. Inside all the zones, the breakdown events and their respective start/end times were determined for all the detector locations. The detector locations that appeared to get congested first were reported as bottleneck locations along the I-4 corridor. A list of all the major bottlenecks, including the potential bottlenecks with their respective breakdown times, is tabulated in Table 4.5.

Table 4.5 List of all bottlenecks along I-4 corridor

Direction	Bottleneck Locations	Breakdown Times
I-4 EB	1) On-ramp from SR-408	7:30 AM
	2) Off-ramp to Kaley St/Off-ramp to SR-408*	7:45 AM; 3:30 PM
	3) On-ramp from Maitland Blvd	4:30 - 5:00 PM
	4) On-ramp from Fairbanks Ave	4:00 - 5:30 PM
I-4 WB	1) On-ramp from Lake Mary Blvd	6:50 - 7:10 AM
	2) On-ramp from SR-436 (Altamonte Springs)	7:00 – 7:15 AM
	3) On-ramp from Maitland Blvd	7:30 – 8:00 AM
	4) On-ramp from Fairbanks Ave*	5:00 – 5:30 PM
	5) Off-ramp to SR-408	3:00 – 5:00 PM

*potential bottlenecks

5 AERIAL RECONAISSANCE

5.1 Introduction

The objective of this task was to conduct an aerial reconnaissance of the I-4 VSL corridor in Orlando, and to collect twenty hours of aerial videos over the I-4 corridor. In general, aerial reconnaissance consists of an aerial survey to collect images and other parameters of a facility. The motivation behind conducting such a study was to identify major bottleneck locations along I-4 and to observe the traffic operations when the VSL system is activated. To accomplish the objective of this task, three activities were performed by the research team, i.e., selecting the contractor for aerial flights; determining appropriate travel times and dates for conducting the aerial survey and summarizing the observations from the surveys. The details of these activities are described next in the report.

5.2 Aerial Flights

5.2.1 Flight Contractor Selection

The first step of this task was to hire a contractor to assist the research team with the aerial videos. The research team contacted several flight contractors that conduct surveys to collect aerial images located in close proximity of Orlando for price quotations. During the initial communications with the contractors, the research team explained each potential contractor about the purpose of the study, and the benefits that it brings in improving the traffic in Orlando. Over a period of two weeks, the research team received several quotations from different vendors to conduct the aerial surveys. The quotations for the aerial flights were primarily based on the hourly cost from the airport base to base.

After the quotations were received, the research team visited several hangar facilities of the respective vendors in Orlando to learn about the aerial video capturing procedure. During these visits, the research team learnt about the other services provided by the respective vendor including the options of a mounted video camera on the nose of the plane or a pre-installed camera inside the plane or helicopter. Although very useful and efficient, the cost of using such equipment was found to be prohibitively high. In the end, the research team decided to select the vendor solely on the basis of the per hour flight cost of the plane.

The vendor that offered the lowest hourly cost, ‘Sun State Aviation Inc.’ located at Kissimmee Airport, was selected to conduct the study. The plane used for the study was a helicopter Robinson-R44-type which could accommodate up to four individuals. As the video equipment were not used from the vendor, the research team decided to use video equipment available at the Transportation Research Center, University of Florida. The video equipment included a set of a handheld camera, cassette tapes, additional camera batteries, a tripod and a monopod.
After the contractor was selected, the research team discussed the potential days for the first aerial flight with the project managers. As the factors influencing the aerial recordings in the study were unclear to both the research team and FDOT, it was decided that the maiden flight could be used as a trial flight for this task. Thereafter, based on the experiences of the trial flight, a more systematic plan could be laid out to complete the remainder of the aerial recordings. The next section describes the trial flight in details, and the outcomes that were drawn from it.

5.2.2 Trial Flight

After the flight contractor was finalized, the research team decided to conduct a trial flight before the other aerial recordings can be conducted. The motivation behind the trial flight was to observe the several factors that may influence the aerial recordings and would eventually help the research team for future aerial sessions. These factors, but not limited to, were the flight’s altitude, the flight’s relative speed as compared to the I-4 traffic, the flight’s steadiness or stability in the air and the flying restrictions in Orlando. For the trial flights, two aerial sessions were planned to be completed as a part of this task, one in the morning and the other in the evening.

The trial flights were conducted on April 13th 2011 from 7 AM – 9 AM in the morning, and from 4 PM – 6 PM in the evening. One of the team members, Vipul Modi recorded the video and was accompanied by FDOT District 5 Engineer, Richard Morrow for the morning session and FDOT District 5 Engineer, Christopher Cairns for the afternoon session. During the course of these flights, the aerial recordings were performed along the I-4 corridor between SR-535 (Vineland Ave) and Lake Mary in both eastbound and westbound directions. The plan was to fly the helicopter along the I-4 corridor from SR-535 to Lake Mary first in the eastbound direction and afterwards from Lake Mary to SR-535 in the westbound direction. While inside the helicopter, the flying team (that included FDOT engineer and research team) discussed the various aspects of I-4 traffic covering the merging/diverging behaviors of vehicles, the in-flow of traffic from on-ramps and more importantly, the locations that appeared to be congested. By the end of the trial flights, roughly four hours of aerial recordings were completed.

The video recordings from the trial flights were extensively reviewed by the research team, and the observations were summarized. The observations/summary of the trial flights is provided in Appendix E of this report under aerial sessions, A1 and A2. A sample video (thirty minutes long) was then shared with the project managers along with the external factors that affected the recordings to obtain their critical and valuable feedback. The feedback was received by the research team over a teleconference call on May 3rd 2011. During the discussions, it became clear that the aerial recordings while traveling along the I-4 corridor would of little value to accomplishing the objective of this task. It was decided that recording the traffic operations at specific bottleneck location on I-4 at specific time of the day would be more valuable than just recording the traffic operations for the entire I-4 corridor. More specifically, it was more valuable to capture the transition scenarios from uncongested conditions to congested conditions, and to identify the various factors that cause/trigger a breakdown or congestion at the respective bottleneck locations. It was suggested that capturing the VSL operations could also be possible by focusing on just specific locations on I-4.

After the discussions with FDOT, the research team scheduled the remaining aerial sessions with the flight contractor. The research team obtained the list of recurrent and potential bottleneck locations on I-4 from the bottleneck identification analysis task of this project. The details from the bottleneck analysis were also used as a guidance to identify the specific times of the day when a breakdown event is more likely to occur. By obtaining the breakdown times, the research team could record the aerial videos prior to the onset of congestion until the queue dissipates at the respective bottleneck location. It was expected that with this approach two aspects of this task would be completed: one is to record aerial videos at each bottleneck location; and the other is to record aerial videos at locations where VSL signs located on I-4 to capture the movements of the vehicles before-and-after the signs. The list of the bottleneck locations and the respective breakdown times are provided in Chapter 4 of this report.

5.2.3 Aerial Flights

After the initial feedback of the trial flight was received from the project managers, the research team scheduled the next sixteen (16) hours of aerial sessions. The aerial sessions were completed on the mornings and evenings of 24th, 25th, 26th of May 2011, the evening of June 7th 2011 and the morning of June 8th 2011. For each day and the respective aerial sessions, the research team prepared a preliminary plan as per the discussions described in the last section. A brief summary of these activities that were performed by each day are listed below:

- *24th May 2011*: Capture the operations at bottleneck locations along the I-4 eastbound direction during both the morning and evening hours
- *25th May 2011*: Capture the operations at bottleneck locations along I-4 westbound direction during both morning and evening hours
- *26th May 2011*: Capture the VSL operations along both I-4 eastbound/westbound directions during morning and evening hours
- *7th /8th June 2011*: Capture the most recurrent bottleneck locations, and identify any other critical factors that affect the I-4 VSL operations

For all the completed flights, one personnel from FDOT District 5 accompanied a member from the UF research team. During the course of all flights, the respective flying team discussed the operations of I-4 corridor and the VSL system. All the discussions were briefly discussed at the end of the flying session, and the notes were summarized. With the completion of the video recordings, the aerial reconnaissance task of this project was completed. It should be noted that during the course of the flights, several external factors resulted in disruptions in the aerial recordings. The most important factors include wind pressure, hand-held camera, Orlando's Executive Airport flying restrictions and the air traffic around Orlando downtown. However, these factors did not necessarily affect the purpose of the aerial flights but resulted in a relatively low quality of videos.

5.3 Observations and major findings

After the aerial recordings were completed, the research team reviewed and analyzed each aerial session to summarize the findings from this task. These findings included the identification of bottlenecks along the I-4 corridor and observations on VSL operations at the corresponding I-4 sections. Seven such major findings were identified in this task. These findings are briefly discussed below, and for each finding a snapshot from the aerial videos is also provided.

1) <u>Bottleneck at I-4 EB: On-ramp from SR-408 WB</u>
    - The high demand for on-ramp from SR-408 WB/EB appeared to cause congestion on the I-4 corridor at South Street during the morning and evening hours. The congestion often resulted in long queues up to Kaley Street along I-4 mainline and also resulted in long queues on the rightmost lane of SR-408 WB. This observation was recurrent over all the aerial sessions at the same time of the day, i.e. 7:20 AM – 7:30 AM.
    - The off-ramp towards Amelia Street also appeared to have high demand during the morning hours. The long queues on the off-ramp also appeared to affect the I-4 mainline operations. Moreover, frequent weaving movements between the on-ramp from SR-408 and the off-ramp to Amelia Street were also observed recurrently.

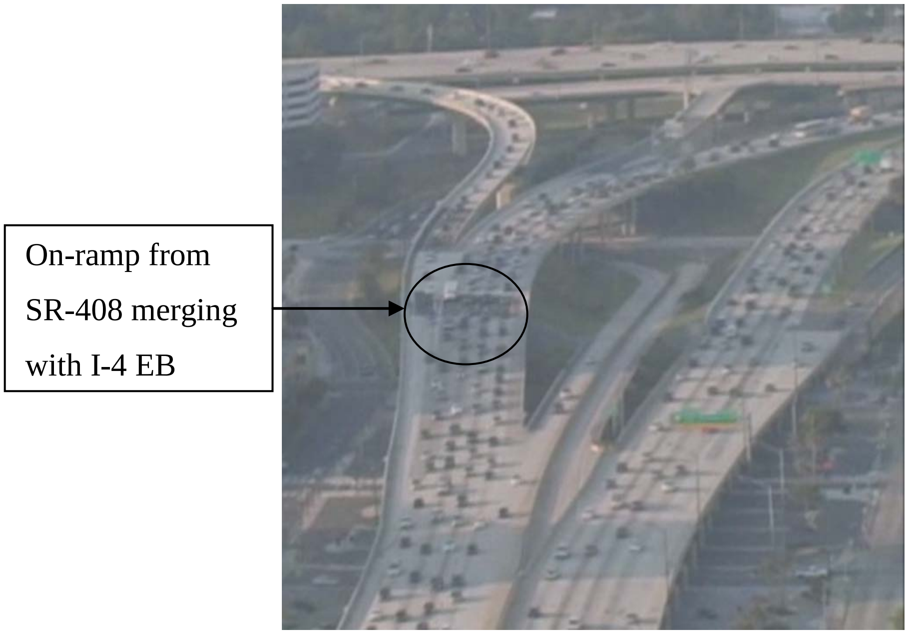
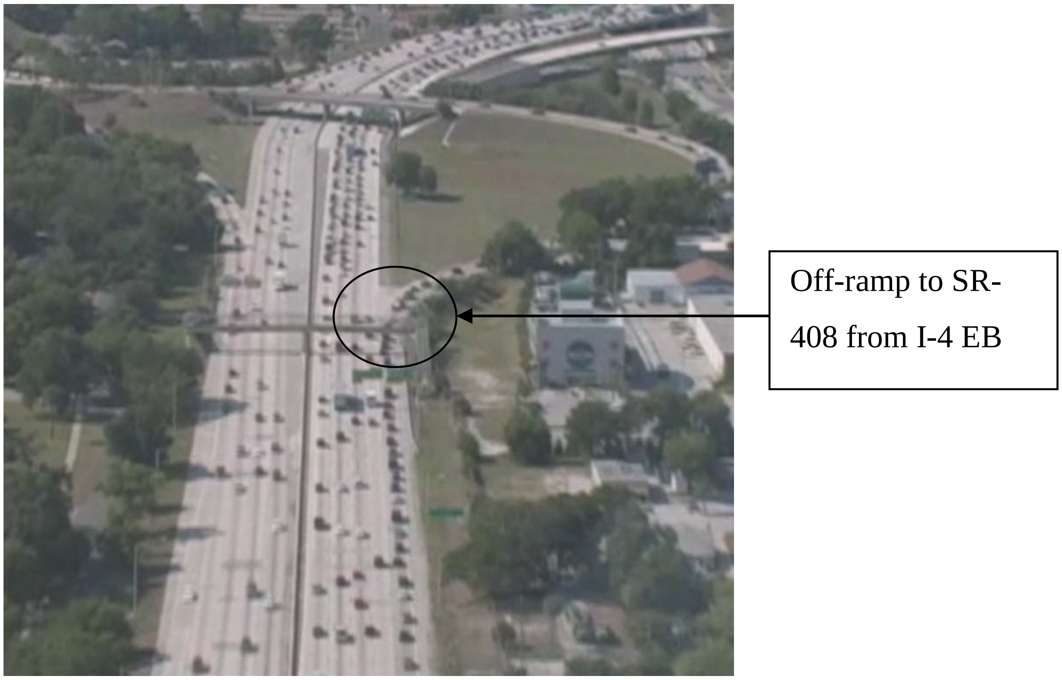


Figure 5.1 Snapshot of the bottleneck located at the merge point of I-4 EB and on-ramp from SR-408 WB

2) Bottleneck at I-4 EB: Off-ramp to SR-408

- The off-ramp to SR-408 from I-4 EB appeared to have heavy demand consistently during the PM peak and sometimes during the AM peak. The long queues at the single lane off-ramp resulted in stop-and-go traffic conditions along the I-4 auxiliary lane. These queues were often observed to extend upstream until Michigan Street.
- After further investigation, it was observed that the off-ramps to SR-408 from both I-4 EB and I-4 WB resulted in formation of long queues on the respective off-ramps.
- The VSL sign board located next to the auxiliary lane at this section does not appear to help in easing the congestion. Multiple aerial sessions reveal that vehicles do not slow down and continue to maintain their original speeds. As a result, the vehicles join the congestion further downstream, and the VSL sign may not be necessarily helping.



Off-ramp to SR-408 from I-4 EB

Figure 5.2 Snapshot of the bottleneck located at the off-ramp for SR-408 from I-4 EB (North angle)

3) <u>Potential Bottleneck at I-4 EB: Off-ramp to Kaley Street</u>

- Heavy demand is observed for the off-ramp to Kaley Street, and long queues appear to form consistently during the AM peak and sometimes during the PM peak. The formation of the queues on the off-ramp was also found to block the incoming traffic from the Michigan Street on-ramp. As a result, congestion is often observed at this section of I-4 corridor.
- The VSL sign located upstream of the off-ramp did not appear to ease the congestion at this section. It also appeared that the VSL sign may have resulted in slow-and-go traffic.

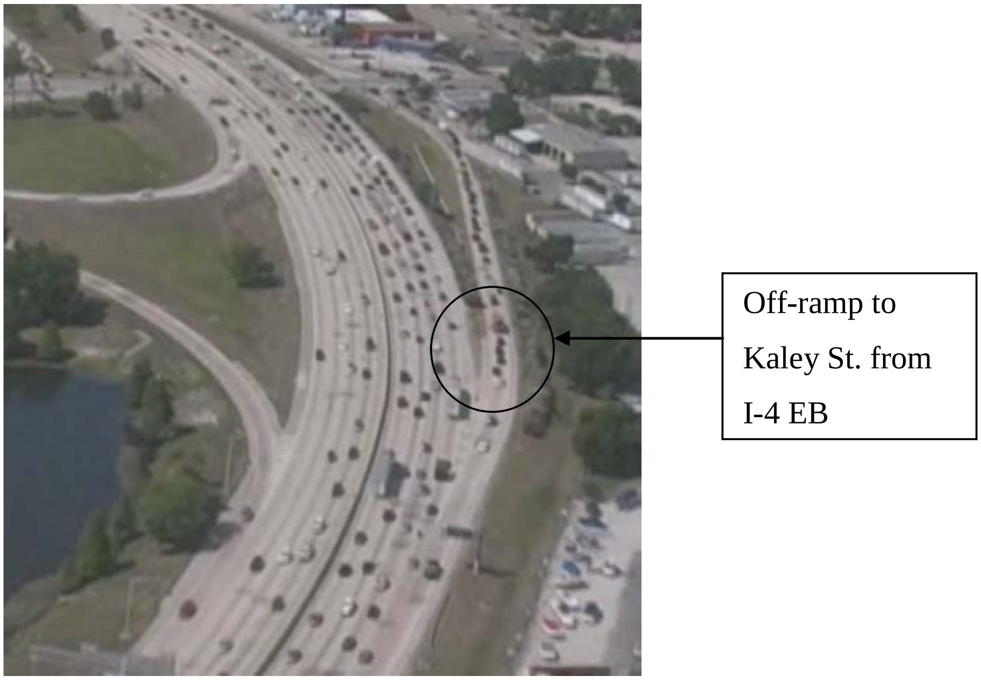
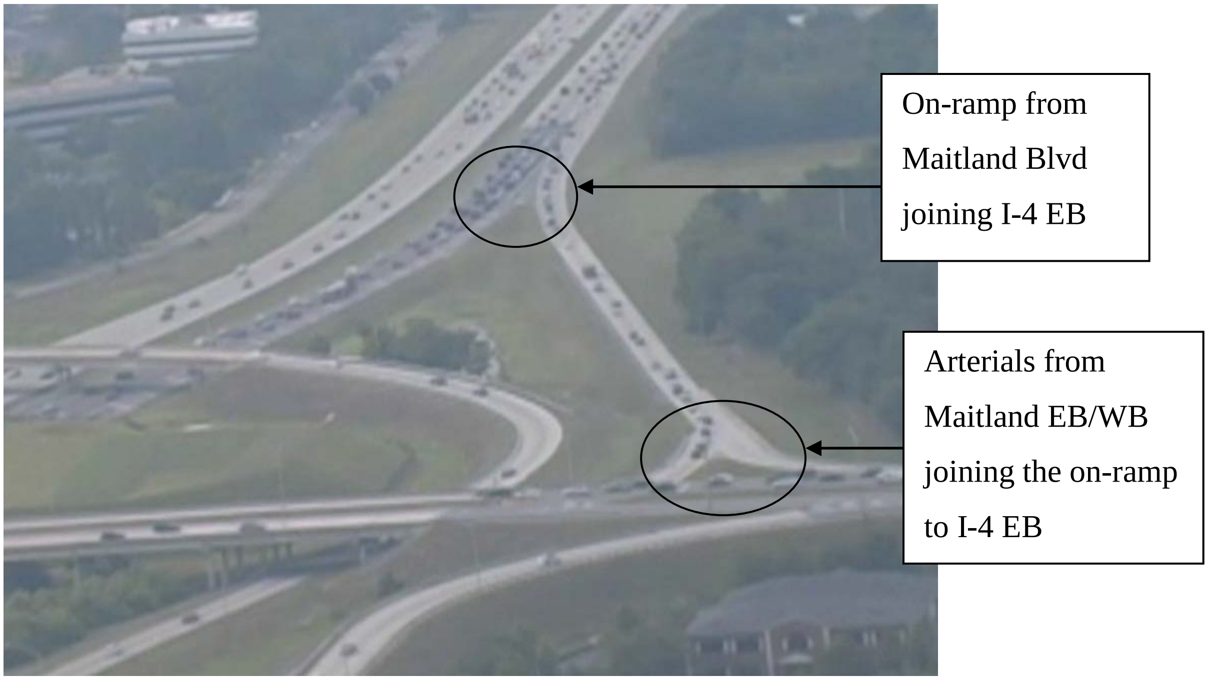


Figure 5.3 Snapshot of the bottleneck located at the off-ramp from I-4 EB to Kaley St. during evening hours

4) Bottleneck at I-4 EB: On-ramp from Maitland Boulevard

- The traffic joining I-4 EB from both EB/WB on-ramps from Maitland Boulevard appeared to create friction and congestion along the I-4 corridor during the PM peak. The surge of vehicles coming from the right turn lane of Maitland Boulevard EB and the left turn lane from Maitland Boulevard WB created friction at the I-4 merging section. The primary reason could be the single lane on-ramp from the respective Maitland Boulevard directions joining the I-4 corridor.
- Long queues appeared on the right most lane of Maitland Boulevard WB direction. Similarly, long queues also appeared on the left turn lane of Maitland Boulevard EB direction.



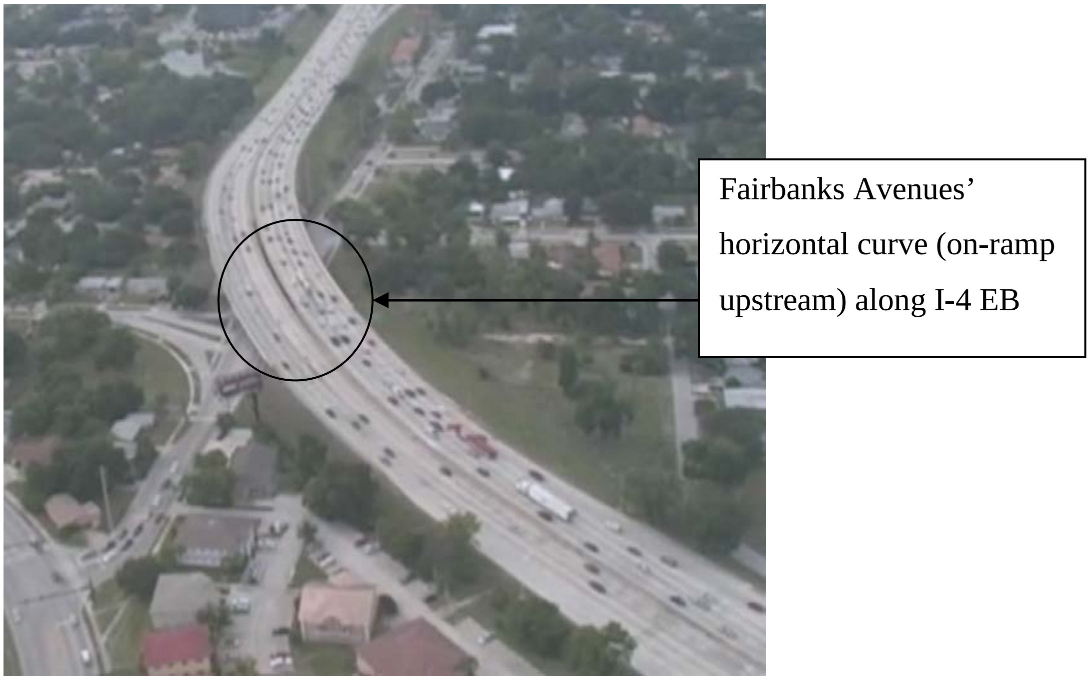
On-ramp from Maitland Blvd joining I-4 EB

Arterials from Maitland EB/WB joining the on-ramp to I-4 EB

Figure 5.4 Snapshot of the bottleneck located east of I-4 and Maitland Blvd interchange

5) <u>Bottleneck at I-4 EB: On-ramp from Fairbanks Avenue</u>

- The on-ramp traffic from the Fairbanks Avenue joining the I-4 EB appeared to cause congestion along I-4. It appeared that the sharp horizontal terrain at the downstream of the on-ramp also resulted in slowing the vehicles.
- As a result of high demand and horizontal terrain, shockwaves were created along the I-4 corridor. The shockwaves appear to travel upstream until Par Avenue.
- The VSL sign located just at the horizontal turn did not appear to ease traffic congestion at this location. The average vehicle speeds were lowered primarily because of the horizontal terrain and not due to the presence of VSL sign board. Also, the presence of trucks at the sharp turn blocked/obstructed the view of the drivers from the speed limit sign boards, which meant that the drivers were not aware of the reduced speed limits.

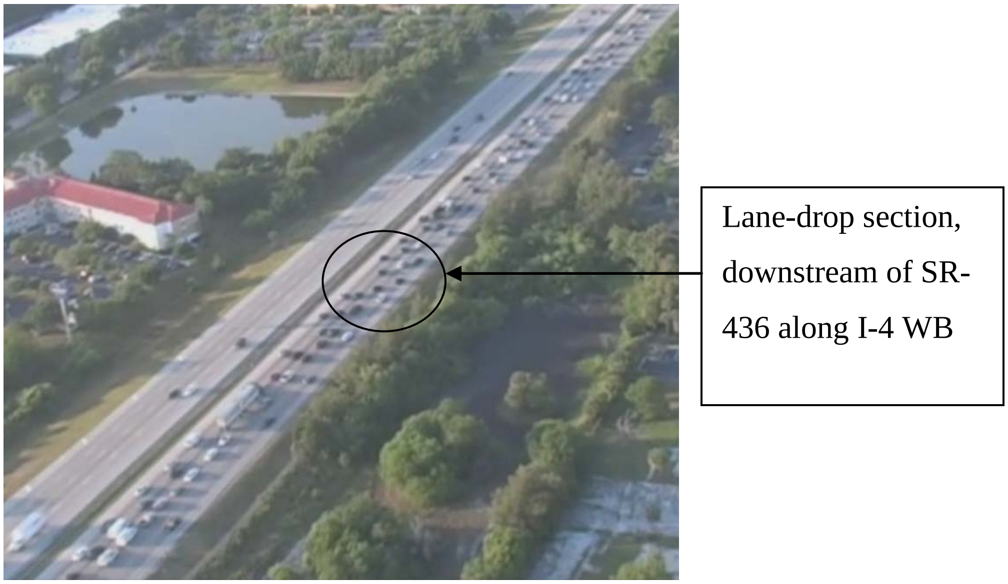


Fairbanks Avenues' horizontal curve (on-ramp upstream) along I-4 EB

Figure 5.5 Snapshot of the bottleneck located near the Fairbanks Avenue

6) <u>Bottleneck at I-4 WB: On-ramp from Altamonte Springs (SR-436)</u>

- The section where the on-ramp from SR-436 joins I-4 WB is found to be congested during early hours of the day due to the presence of a lane drop further downstream. It appeared that the vehicles on the acceleration lane did not tend to change the lanes at the first available gap but appeared to travel all the way till acceleration lane ended. This resulted in congestion on the rightmost lane.
- Similarly, the lane drops at the locations downstream of Lake Mary Boulevard and SR-434 were also found to be congested during the morning hours.



Lane-drop section, downstream of SR-436 along I-4 WB

Figure 5.6 Snapshot of the bottleneck located west of SR-436 along I-4 WB

7) Bottleneck at I-4 WB: Off-ramp to SR-408

- Long queues appeared to form at the off-ramp to SR-408 from I-4 WB direction in the evening hours. The formation of the queues at the off-ramp results in congestion along I-4 mainline till Ivanhoe Boulevard.
- It was also interesting to observe that the off-ramps from I-4 EB and WB merge with each other before leading towards SR-408. The weaving movement at this location results in formation of queues along both I-4 off-ramps. The off-ramps subsequently congest the I-4 mainline. Therefore, the merging point of the off-ramps appears to be a major bottleneck location for the I-4 corridor.

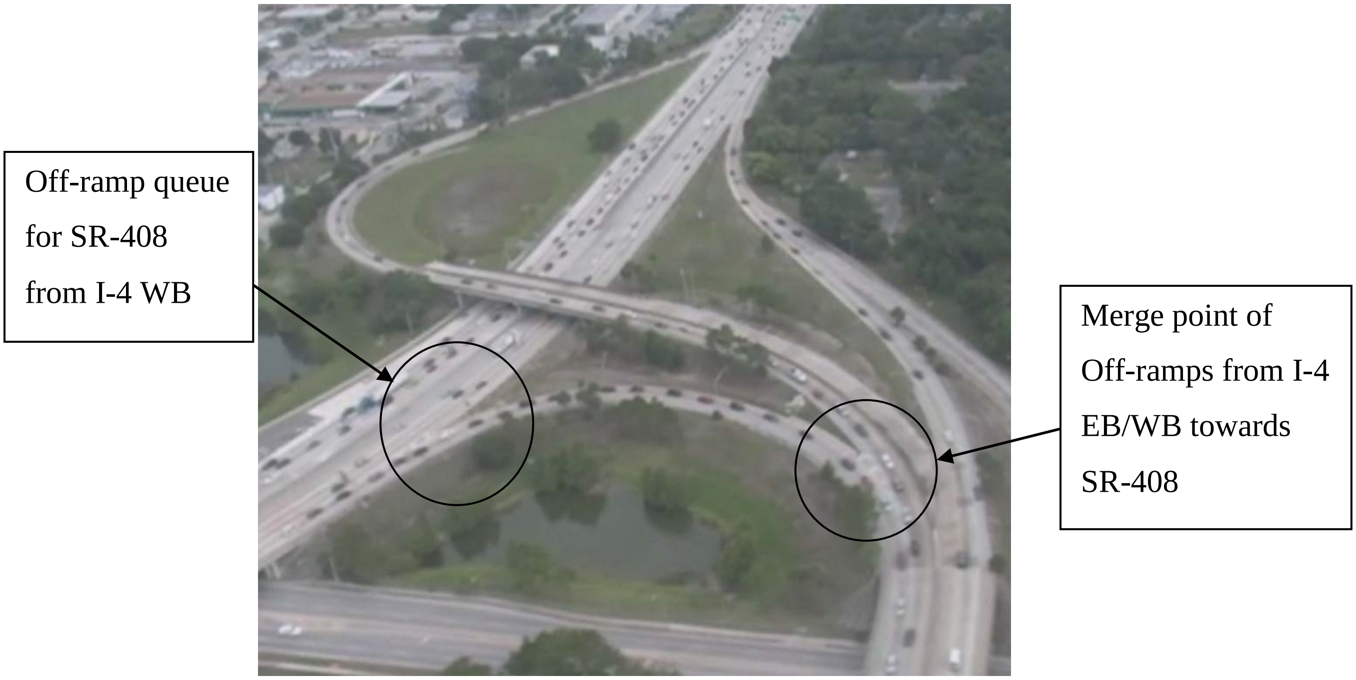


Figure 5.7 Snapshot of the bottleneck located at the off-ramp to SR-408 from I-4 WB

The findings as discussed above were shared with the project managers over a teleconference call on August 15th2011. In this meeting, the project managers recommended the research team that providing a summary of each aerial session would be most suitable and appropriate for this task. Therefore, a detailed summary of each aerial session is also included in this report in Appendix E. In all, ten aerial sessions and twenty hours of aerial videos were reviewed and summarized. These summaries also include the feedback, comments and observations received to the research team from the FDOT personnel present in the respective flight session. Each section of the Appendix E indicates the session number, the date/time of flight, and the name of the FDOT personnel on board during the respective aerial flight session.

5.4 Aerial Videos

At the end of the aerial reconnaissance task, the research team produced twenty hours of video recordings covering the important aspects of I-4 operations. As part of the final deliverables for this project, the aerial videos in DVDs were sent to the project managers in March 2012. Next, it was also advised that a summary of each video clip would be useful to the project managers and the FDOT team for future reference. Therefore, the research team reviewed the aerial videos extensively and summarized the important events from each video clip. A comprehensive table indicating the times on the video clips and the respective observations from the twenty hours of video recordings was prepared and is provided in Tables 5.1 – 5.5.

Table 5.1 Summary of video clips for the aerial sessions A1 and A2

Video Details				**Description**	
Aerial Session		**Date**	**Time on Video**	**Direction**	**Clip Details**
A1	Morning Part 1	4/13/2011	Start - 32:00	I-4 EB	Traffic operations along I-4 EB
			19:18 - 21:00	I-4 WB	I-4 WB congested with on-ramp traffic from SR-434
			23:00 - 32:00	I-4 WB	I-4 WB congested with on-ramp traffic from Lake Mary Blvd
			42:00 - 46:00	I-4 EB	I-4 EB congested with on-ramp traffic from SR-408 till OBT
	Morning Part 2	4/13/2011	3:00 - 7:00	I-4 EB	I-4 EB congested from OBT till SR-408 Interchange
			13:00 - 15:00	I-4 EB	Long queues for Maitland Blvd from I-4 EB
			15:30 - 17:45	I-4 WB	I-4 WB congested with on-ramp traffic from SR-436
			18:00 - 25:00	I-4 WB	I-4 WB congested with on-ramp traffic from SR-434 till Lake Mary Blvd
			32:00 - 36:00	I-4 WB	I-4 WB congested with on-ramp traffic from SR-436
					I-4 WB congested with on-ramp traffic from SR-434
			42:30 - 46:00	I-4 EB	I-4 EB corridor congested from Amelia St. off-ramp to Kaley St. off-ramp
A2	Evening Part 1	4/13/2011	9:00 - 14:00	I-4 EB	I-4 EB congested from CR-423 till Ivanhoe Blvd
				I-4 WB	I-4 WB congested from SR-408 till Ivanhoe Blvd
			15:45 - 21:00	I-4 EB	I-4 EB congested from Fairbanks Ave till Maitland Blvd
			32:30 - 37:30	I-4 EB	I-4 EB congested from Maitland Blvd till Fairbanks Ave
			37:00 - 40:00	I-4 WB	I-4 WB congested from Par St. till SR-408
			38:00 - 43:00	I-4 WB	I-4 EB congested from Ivanhoe Blvd till CR-423
	Evening Part 2	4/13/2011	7:30 - 10:00	I-4 EB	I-4 EB corridor congested from OBT till off-ramp to Amelia St.
			30:30 - 32:30	I-4 EB	I-4 EB congested at merging point with on-ramp from Maitland Blvd
					Long queues on Maitland Blvd EB/WB arterials
			36:00 - 38:00	I-4 WB	Long queues for SR-408 from I-4 WB leading to congestion till Ivanhoe Blvd
			37:30 - 39:30	I-4 EB	I-4 EB corridor congested from SR-408 till OBT (including off-ramp to Kaley St.)

Table 5.2 Summary of video clips for the aerial sessions A3 and A4

Video Details				Description	
Aerial Session		**Date**	**Time on Video**	**Direction**	**Clip Details**
A3	Morning Part 1	5/24/2011	5:00 - 6:00	I-4 WB	High Demand from SR-408 onto I-4 WB
			7:00 - 26:00	I-4 EB	Queues over off-ramp to Amelia St., and congestion at SR-408/I-4 EB merge locations
			26:00 - 39:00	I-4 EB	Off-ramp to Kaley St. congested
			46:00 - End	I-4 EB	Long queues from Maitland EB/WB for I-4 EB
	Morning Part 2	5/24/2011	1:20 - 11:00	I-4 WB	On-ramp from SR-434 onto I-4 WB congested
			11:00 - 14:00	I-4 WB	On-ramp from SR-436 onto I-4 WB congested
			19:30 - 21:00	I-4 WB	High demand for off-ramp to SR-50 from I-4 WB
					VSL operations for sign located at Ivanhoe Blvd, vehicles may be slowing down
			21:30 - 24:30	I-4 WB	High demand for I-4 WB from SR-408
			24:30 - End	I-4 EB	Traffic operations from SR-408 till OBT, and congested I-4 corridor
A4	Evening Part 1	5/24/2011	0:25 - 1:10	I-4 EB	Long queues for SR-408 from I-4 EB
			1:15 - 14:00	I-4 EB	Congestion at merging point of I-4 EB and on-ramp from SR-408
			35:00 - 43:00	I-4 EB	Long queues for SR-436
					Congestion downstream due to presence of an emergency vehicle
			45:10 - 47:20	I-4 EB	Congestion at merging point of I-4 EB and on-ramp from Maitland Blvd
			47:20 - End	I-4 EB	Congestion on arterial Maitland Blvd (EB/WB)
	Evening Part 2	5/24/2011	Start - 5:00	I-4 EB	Upstream of Maitland Blvd/I-4 EB gets congested (long off-ramp queues)
			5:00 - 19:00	I-4 EB	Fairbanks Ave./I-4 EB interchange gets congested (on-ramp demand)
			19:30 - 23:00	I-4 WB	VSL sign near Ivanhoe Blvd showing 40 mph with downstream congestion
			23:00 - 25:30	I-4 EB	I-4 EB congested at on-ramp from SR-408
					Long queues for SR-408 from I-4 EB, Inside lanes stopped and outside lanes moving
			25:30 - 33:00	I-4 EB	I-4 EB congested from Kaley St. till OBT
			33:00 - 35:00	I-4 WB	I-4 WB congested at off-ramp for Florida Turnpike

Table 5.3 Summary of video clips for the aerial sessions A5 and A6

Video Details				Description	
Aerial Session		Date	Time on Video	Direction	Clip Details
A5	Morning Part 1	5/25/2011	19:00 - 22:30	I-4 WB	Heavy demand from Lake Mary Blvd onto I-4 WB
			23:00 - 25:30	I-4 WB	I-4 congested at merging point from SR-434 (lane drop)
			25:30 - 53:57	I-4 WB	Traffic operations between SR-436, Maitland Blvd and Lee Rd over I-4 WB
					I-4 congested at merging point from SR-436 (lane drop)
					Heavy demand from Maitland Blvd and Lee Rd onto I-4 WB
	Morning Part 2	5/25/2011	5:00 - 20:00	I-4 WB	Traffic operations between Maitland Blvd and Lee Rd
			1:00:00 - End	I-4 EB	I-4 congested where on-ramp from SR-408 joins
A6	Evening Part 1	5/25/2011	2:30 - 5:25	I-4 EB	I-4 EB congested from Rio Grande till SR-408 interchange
				I-4 EB	Off-ramp to Kaley St. congested
			6:10 - 10:30	I-4 EB/WB	Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
			13:00 - 40:00	I-4 EB	VSL operations for VSL sign located downstream of OBT
					Formation of queues with VSL active
			40:30 - 51:00	I-4 EB	VSL operations for VSL sign located downstream of Kaley St.
					VSL sign shows 40 mph with downstream congested
			51:00 - End	I-4 EB	VSL operations for VSL sign located at Ivanhoe Blvd
	Evening Part 2	5/25/2011	2:00 - 9:00	I-4 EB	I-4 congested at downstream of Maitland Blvd
					High demand from off-ramps onto I-4 EB
			16:00 - 28:00	I-4 EB	I-4 congested at downstream of Maitland Blvd (Contd…)
					High demand from off-ramps onto I-4 EB (Contd…)
			28:00 - 39:00	I-4 EB	VSL operations at sign located downstream of Fairbanks Ave.
			45:00 - 47:00	I-4 WB	I-4 congested between Par St. and SR-408 along WB
			46:00 - 51:00	I-4 EB	I-4 congested between SR-408 and CR-423

Table 5.4 Summary of video clips for the aerial sessions A7 and A8

Video Details				**Description**	
Aerial Session		**Date**	**Time on Video**	**Direction**	**Clip Details**
A7	Morning Part 1	5/26/2011	15:15 - 29:00	I-4 WB	I-4 congested at merging point from SR-436 (lane drop)
			29:00 - 32:00	I-4 WB	Heavy demand from Maitland Blvd and Lee Rd onto I-4 WB
			34:00 - 38:00	I-4 EB/WB	VSL operations for sign located at Ivanhoe Blvd along I-4 EB/WB
			38:00 - 55:00	I-4 EB	I-4 EB congested at on-ramp from SR-408 (long queues for Amelia St)
					VSL operations for sign located at Kaley St.
			56:00 - 59:00	I-4 EB/WB	Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
	Morning Part 2	5/26/2011	Start - 7:00	I-4 EB	Congestion upstream of I-4 and SR-408 merging point
			7:00 - 14:00	I-4 EB	Congestion on I-4 from SR-408 till OBT
					VSL operations at OBT (VSL sign showing 30 mph)
					I-4 WB off-ramp to Michigan Ave. causes friction on mainline
			15:00 - 20:00	I-4 EB	I-4 EB congested at on-ramp from SR-408
					Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
			32:00 - 35:00	I-4 WB	I-4 congested at merging point from SR-436 (lane drop)
A8	Evening Part 1	5/26/2011	3:20 - 10:30	I-4 EB/WB	Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
			10:30 - 20:30	I-4 EB	VSL operations at OBT (VSL sign showing 40 mph)
			21:00 - 38:00	I-4 EB	Traffic operations between SR-408 and OBT along I-4 EB
					Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
	Evening Part 2	5/26/2011	Start - 8:00	I-4 WB	Off-ramp queues for SR-408 from I-4 WB leads to congestion till Ivanhoe Blvd
			12:00 - 22:00	I-4 WB	VSL operations for sign located at Ivanhoe Blvd
					Formation of queues, vehicles may not be slowing

Table 5.5 Summary of video clips for the aerial sessions A9 and A10

Video Details				Description	
Aerial Session		Date	Time on Video	Direction	Clip Details
A9	Evening Part 1	6/7/2011	5:45 - 6:30	I-4 EB/WB	Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
			8:30 - 20:00	I-4 EB/WB	VSL operations for sign located at Ivanhoe Blvd (EB/WB)
			35:00 - 45:00	I-4 EB/WB	VSL operations for sign located at Ivanhoe Blvd (EB/WB)
			46:00 - 47:00	I-4 EB/WB	Off-ramps from I-4 EB/WB for SR-408 conflicts leading to congestion at I-4 EB/WB
			47:00 - 51:00	I-4 EB	I-4 EB congested at on-ramp from SR-408
					VSL operations for sign located at OBT
	Evening Part 2	6/7/2011	4:30 - 16:00	I-4 EB	Traffic operations at merging point of I-4 EB and on-ramp from Maitland Blvd
					Formation of queues on arterials leading to on-ramp
			16:00 - 35:00	I-4 EB	VSL operations at sign located at downstream of Fairbanks Ave
			36:00 - 43:00	I-4 EB	VSL operations for sign located at Ivanhoe Blvd (EB/WB)
			43:00 - End	I-4 WB	Long queues for off-ramp to SR-408 from I-4 WB leads to congestion till Ivanhoe Blvd
A10	Morning Part 1	6/8/2011	Start - 9:00	I-4 EB/WB	Traffic operations along I-4 EB/WB
			15:15 - 33:00	I-4 WB	I-4 congested at merging point from SR-436 (lane drop), and upstream congestion
					I-4 congested at merging point from SR-434 (lane drop)
			40:00 - 40:30	I-4 WB	Queues for SR-50 from I-4 WB
			46:00 - End	I-4 EB	Transition of uncongested conditions to congested conditions at I-4 EB/SR-408
	Morning Part 2	6/8/2011	Start - 6:00	I-4 EB	I-4 corridor congested at merging point with on-ramp SR-408 WB
			10:20 - 11:10	I-4 EB	High demand for off-ramp to Kaley St from I-4 EB
			31:40 - 48:00	I-4 WB	I-4 congested at merging point from SR-436 (lane drop)
					I-4 congested at merging point from Maitland Blvd

5.5 Summary

The research team conducted the aerial reconnaissance task of this project by recording aerial observations of bottleneck locations along I-4 and by capturing the effects of the VSL system in easing the downstream traffic. A flight company was hired to carry out aerial flights, and twenty hours of aerial observations were recorded along the I-4 corridor. Each aerial session included a member from the UF research team and personnel from FDOT District 5 office.

The major findings from this task were the identification and/or confirmation of bottlenecks along the I-4 eastbound and I-4 westbound directions. The on-ramp from SR-408 westbound joining the I-4 eastbound was found to be the major source of congestion along the I-4 eastbound corridor. On the other hand, it appeared that bottlenecks along the I-4 westbound direction are present, but they are located outside the current VSL zone. These are downstream of on-ramps from Lake Mary Boulevard, Altamonte Springs, and SR-434. Lastly, the off-ramps to SR-408 from both I-4 eastbound and westbound appeared to conflict with each other, resulting in formation of long queues over the respective I-4 directions. A detailed summary of the aerial sessions is also provided with details on the video clips indicating the most important events from the aerial sessions.

6 DEVELOPMENT OF OPERATIONAL IMPROVEMENTS AND RECOMMENDATIONS

This chapter describes the research efforts to build a CORSIM simulation model of the I-4 VSL zone and evaluate various potential VSL algorithms and their respective settings. The scenarios evaluated pertain to changes in the VSL algorithms, sign locations, detector locations, as well as an evaluation of the impact of driver compliance on traffic operations. The outcome of this task is an assessment of the effectiveness of various VSL-related strategies and algorithms to improve traffic operations along the I-4 VSL zone.

This chapter provides first a description of the freeway facility examined and the simulation model developed, followed by the process and results of calibration to ensure the CORSIM simulation adequately replicates operations along this facility. The third subsection discusses the simulation scenarios tested along with the respective results and findings.

6.1 The I-4 Orlando Freeway Facility

The section of I-4 examined is located between Rio Grande Ave. and Maitland Blvd. in the eastbound direction. There are a total of eight VSL sign locations along this stretch, each linked to two or three different detector locations. Figure 6.1 shows an aerial view of I-4 with the sign locations identified.

A CORSIM network was created to replicate the current conditions on I-4 in the eastbound direction. The geometry of the roadway was created based on information from aerial photography and as-built drawings. The nodes and links were overlaid on top of this image. A snapshot of the CORSIM network is displayed in Figure 6.2.

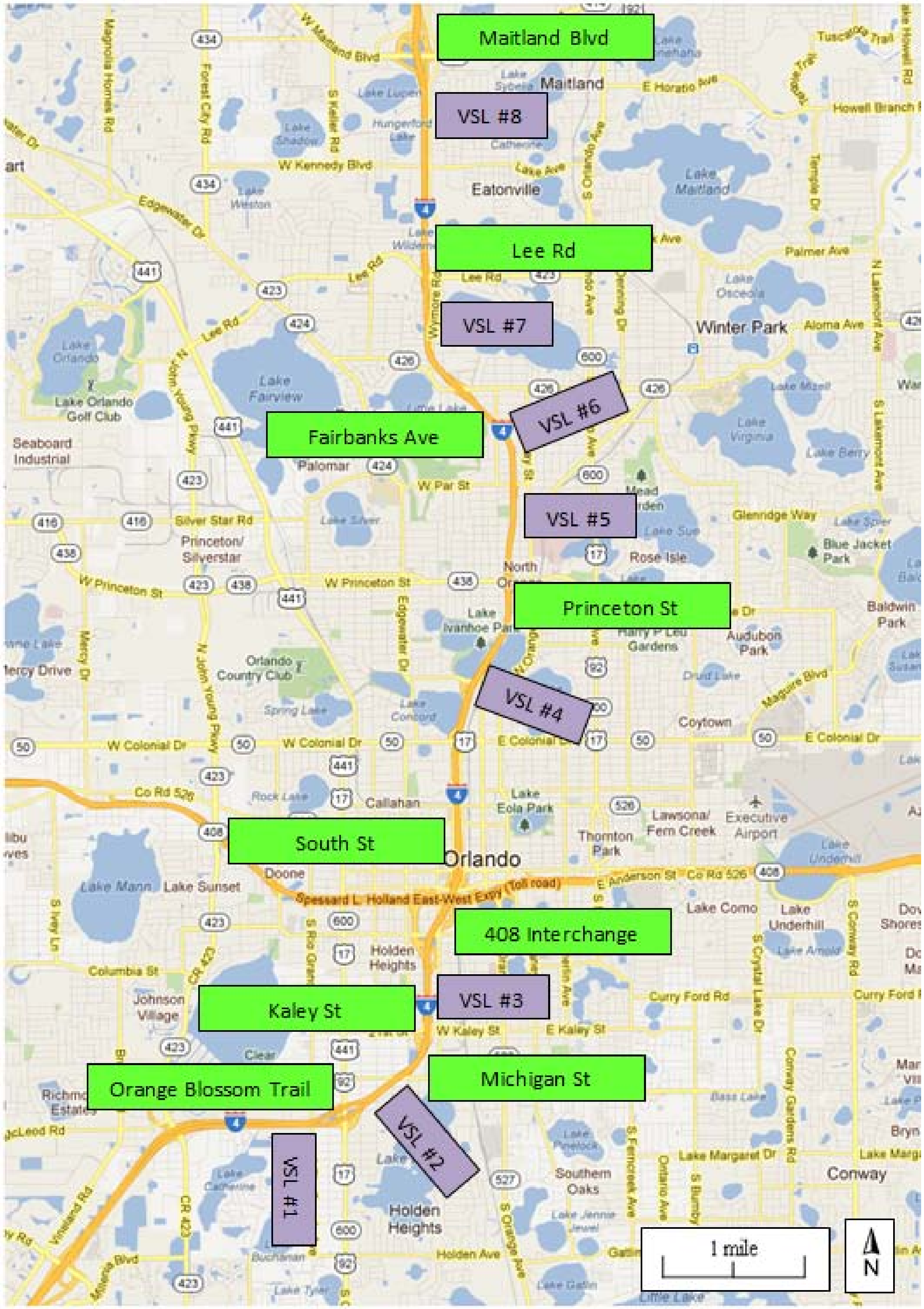


Figure 6.1 Aerial view of I-4 and VSL sign locations

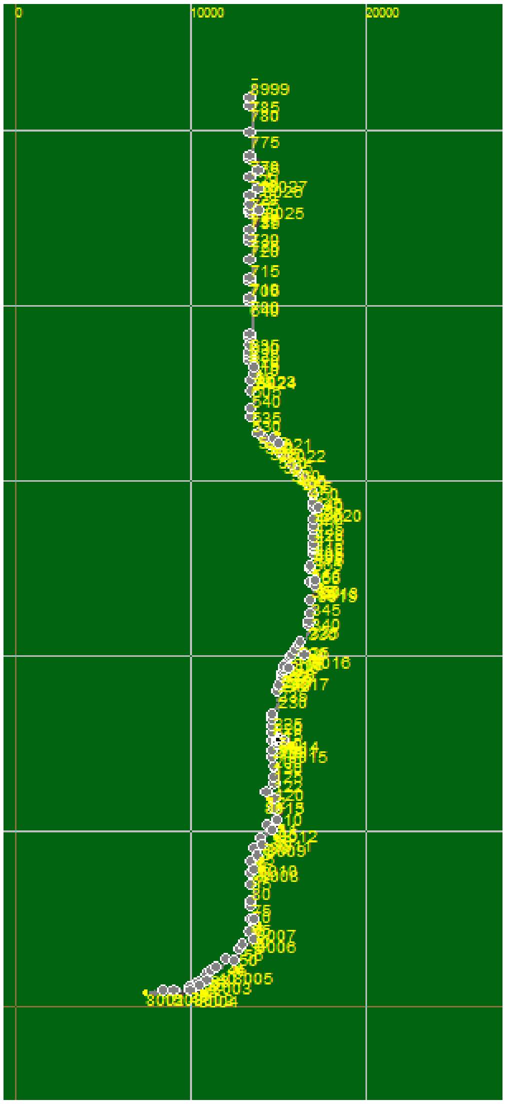


Figure 6.2 Snapshot of the I-4 CORSIM network

A schematic detailing the CORSIM network geometry is shown in Figure 6.3. The schematic shows all nodes and links in the network, including lane and ramp configuration. The lengths of links and ramps are shown along with the grade and radius of curvature. Notable cross-streets are shown on the schematic for reference. The location of all the VSL signs and detectors currently utilized along the freeway are noted in the schematic.

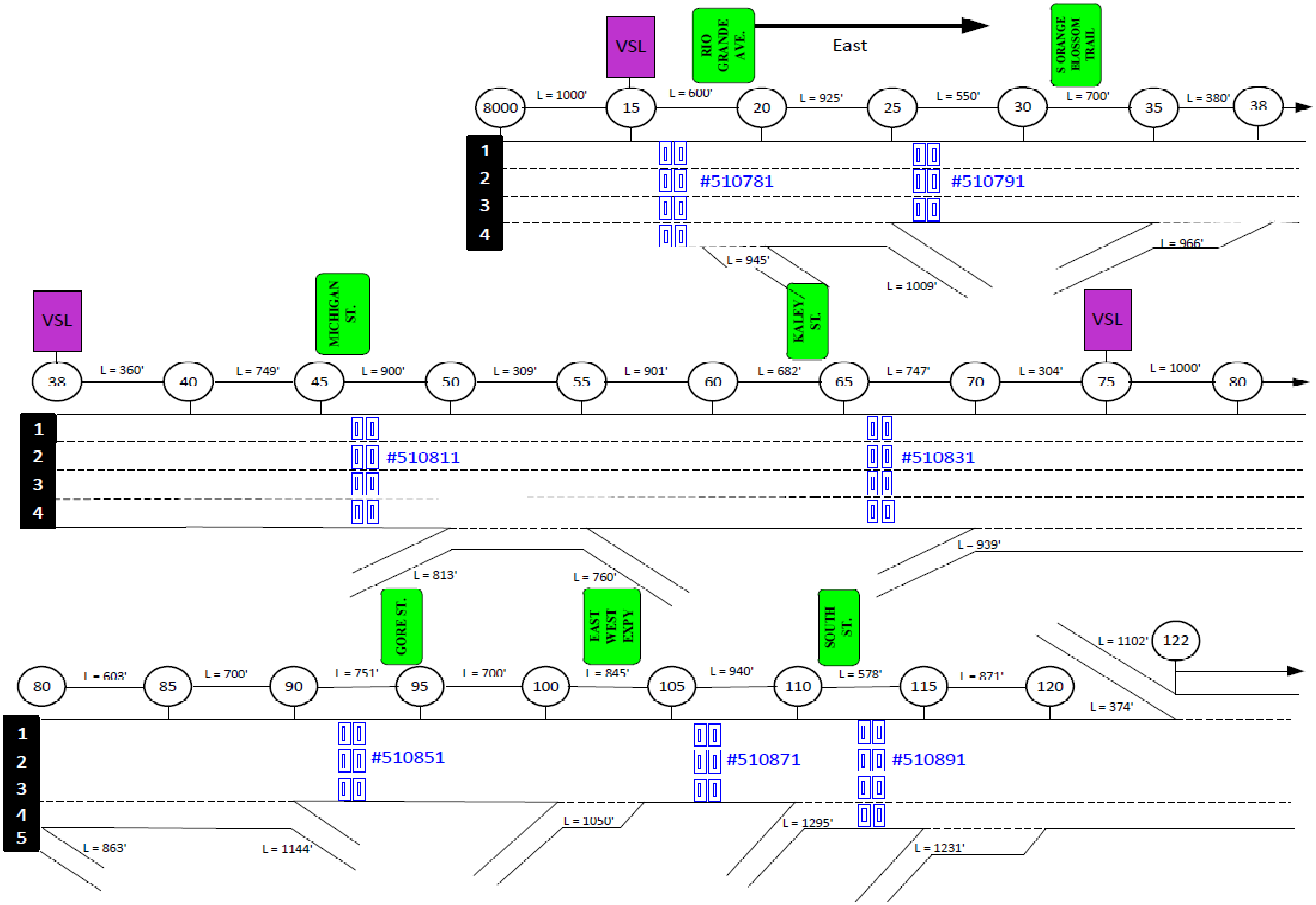


Figure 6.3 Detailed schematic of the I-4 CORSIM network

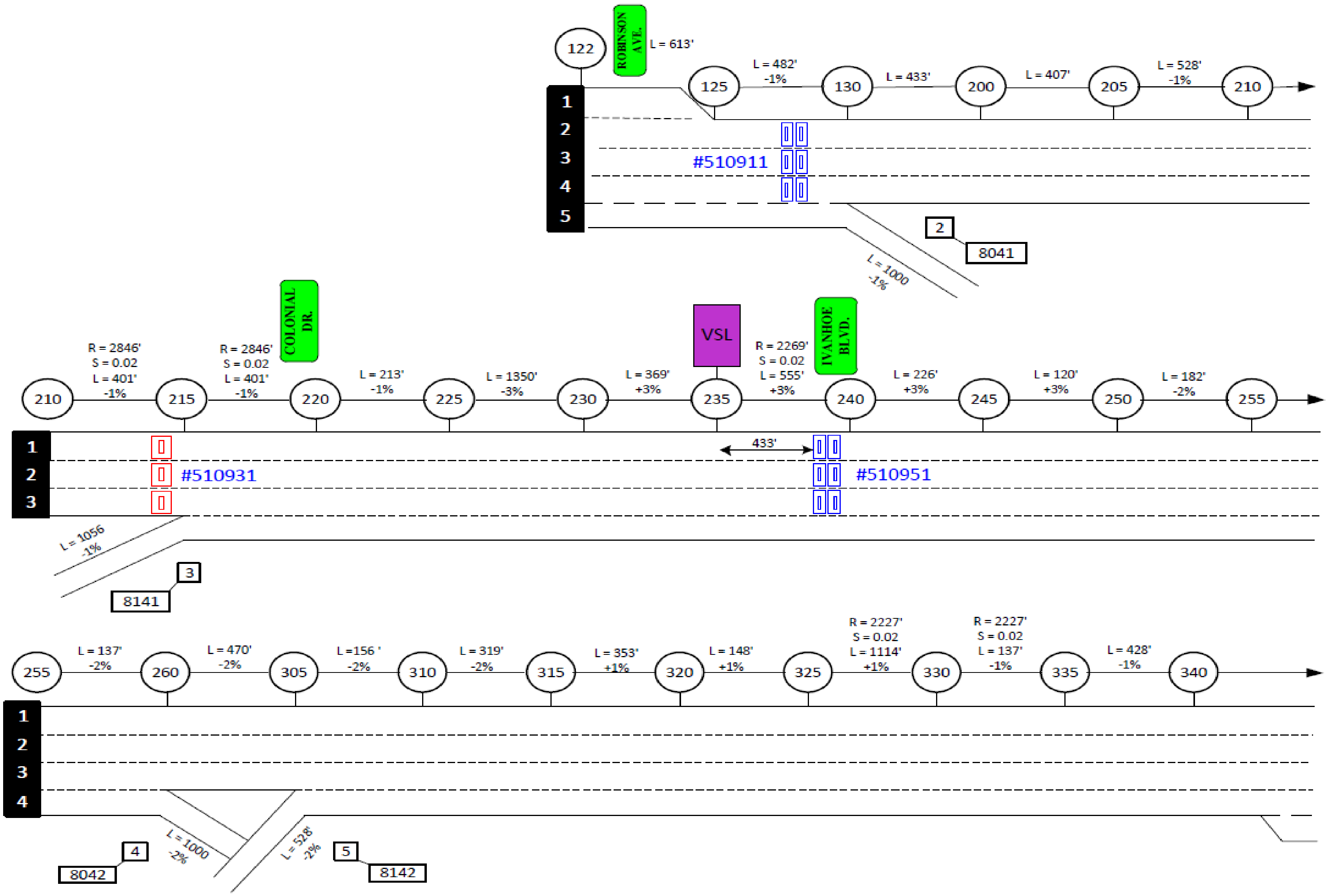


Figure 6.3 Detailed schematic of the I-4 CORSIM network (continued).

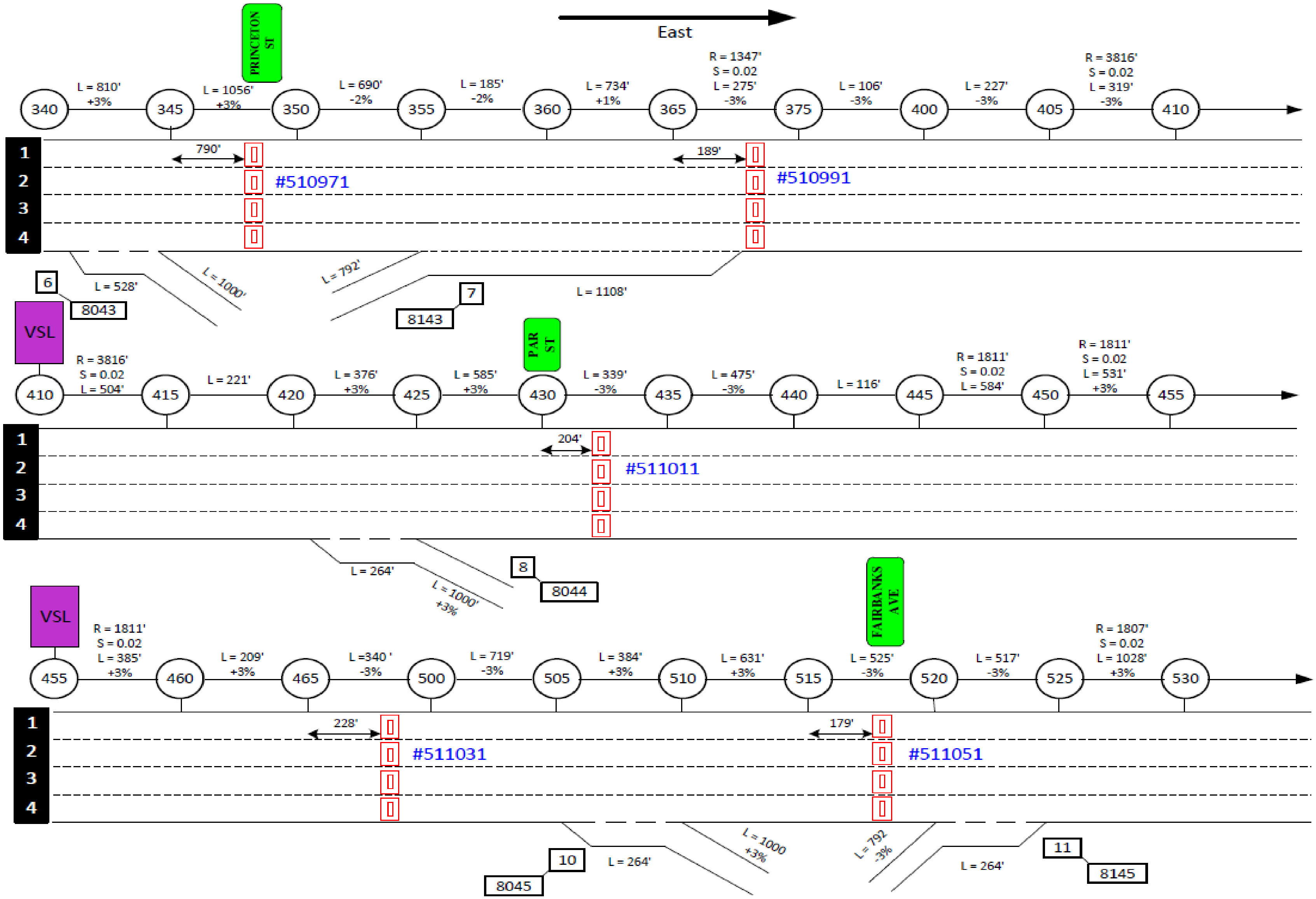


Figure 6.3 Detailed schematic of the I-4 CORSIM network (continued).

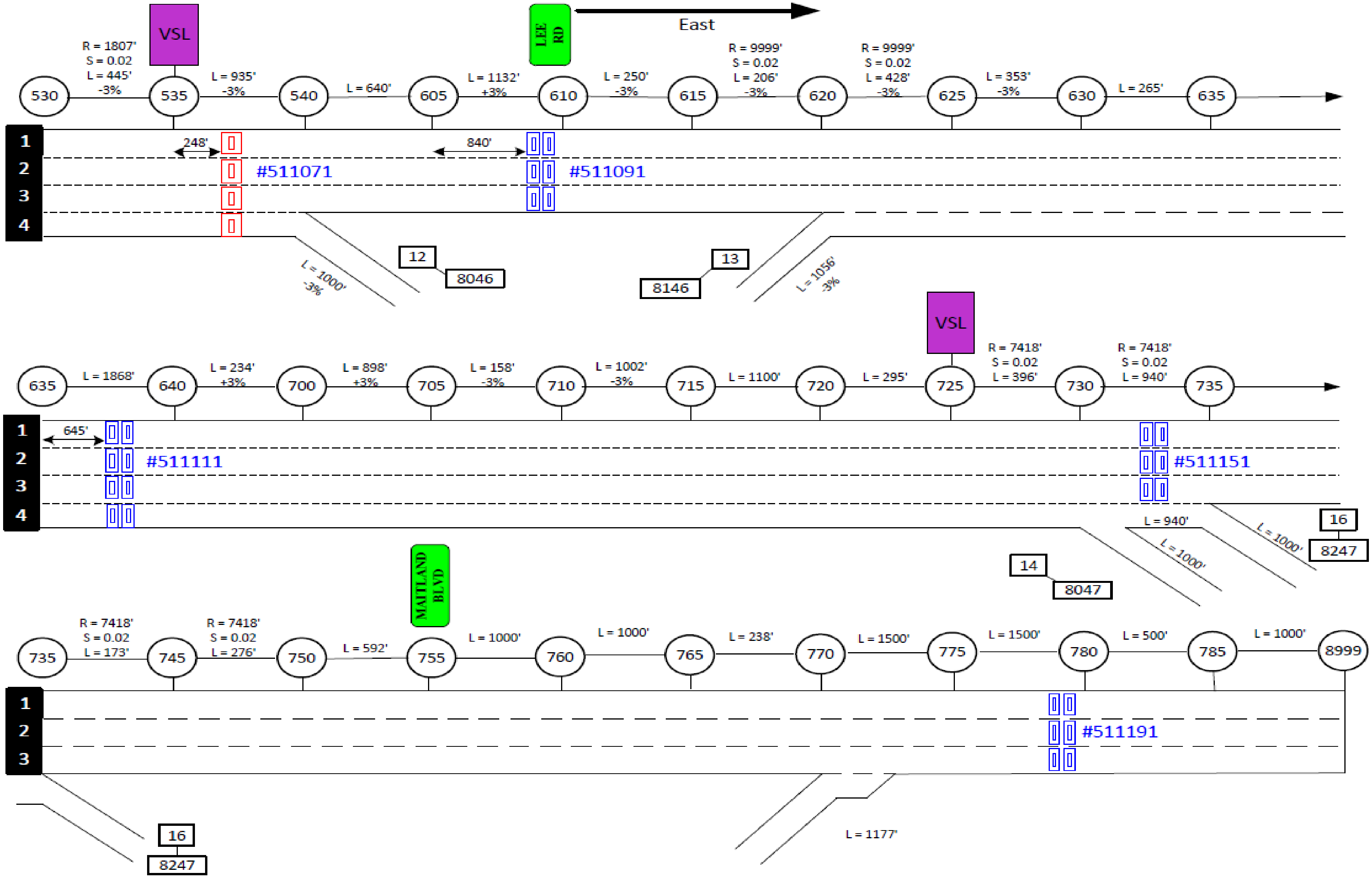


Figure 6.3 Detailed schematic of the I-4 CORSIM network (continued).

6.2 Calibration Process

During this step, the simulation model developed was calibrated to match a typical day of field data to ensure the model is accurately replicating the traffic operating conditions of the network, including the locations, timing, and extent of congestion. If the simulation is accurately replicating the field conditions, then it can be assumed that any operational changes made in the simulation would display similar trends in the field.

The I-4 CORSIM network was calibrated to match average speeds and volumes based on one day of data from May 24th, 2011 and for the hours of 7:00 AM to 10:00 am (am peak in the eastbound direction). This day is considered a typical day, since it is a normal weekday (Thursday), and follows the traffic operational patterns discussed in Chapter 4. The field data were obtained from the STEWARD database which aggregates and compiles daily detector information. Volumes were obtained in 15-minute intervals, thus the simulation contains a total of 12 analysis periods. The 18 detectors used for calibration are the same detectors identified in Figure 6-3. In addition to the data from detectors, the aerial video taken on May 24th, 2011 was used to confirm all the simulated ramp queues were forming at the same locations as in the field.

The following assumptions were made in the modeling and calibration of the network. Since no vehicle-specific traffic counts were available, the entire network was assumed to operate with 4% heavy vehicles. Many of the on and off-ramp volumes were extracted from the STEWARD database when detectors were located directly upstream and downstream of the subject ramp. In those cases it was assumed that the ramp flow is equal to the difference between the upstream and the downstream flow. However, in some cases there were two or three ramps in between detector locations. In this case reasonable assumptions were made regarding the entering and exiting volumes of these ramps.

To accurately replicate the traffic operations on I-4, the model was calibrated utilizing the current VSL operating strategy. A Run Time Extension (RTE) was created that mimics the current I-4 VSL operation, and the entire calibration procedure was carried out using this supplemental program which interfaces directly with CORSIM. Detailed information regarding the operation of the RTE is described later in the chapter in conjunction with the discussion of each VSL scenario tested.

Since CORSIM is a stochastic simulator, it uses random number generators to replicate traffic conditions, and each run should be viewed as one sample of the experiment. Thus, several runs of the simulator are needed to obtain an estimate of the "average" conditions in the network. Initially, the model was loaded with a base flow volume and was executed 10 times. The average network speed was obtained and is shown in Table 6.1. Assuming an allowable error of e=0.05 mph and 95% confidence level, the required number of runs was estimated to be 7. Thus, in subsequent analysis 10 runs are conducted which are more than adequate for the project purposes.

Table 6.1 Average network speed for each simulation run

Run #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Average Network Speed (mph)	45.63	47.09	47.31	46.43	47.77	47.53	45.15	46.61	46.43	48.12

An iterative process was performed to calibrate the simulation network. Starting at time period one, on-ramp volumes and off-ramp percentages were altered to match the field data at the identified detectors. This iterative process continued until volumes and speeds were matched for that time period. This process was carried out for every subsequent time period, until the simulation matched speed and volumes for all 12 time periods. Various adjustments were also made to ensure the formation of ramp queues was appropriate. In order to replicate the formation and propagation of the bottleneck, other parameters were adjusted as well. The calibration parameter with the most profound effect on the simulated traffic operations was found to be the car-following sensitivity factor. This factor determines the desired time headway during car-following. Parameters affecting the lane changing activity and the arrival rate of traffic into the network were also adjusted.

The results of the calibration can be found in Appendix F. The simulation results were compared directly to the field data. Overall, the simulation volumes and speeds match very closely the field data. Simulation volumes and speeds are nearly identical to field data through the first four time periods. During congested conditions the simulation speeds match the field speeds nearly identically, however the volumes in the simulation are typically higher during this period of congestion (Time Periods 5 through 7). During the recovery phase (Time Periods 8 through 10), the volumes again match nearly perfectly, however the simulation speeds show a faster recovery than in the field. These discrepancies can be attributed to the inherent limitations of the CORSIM software, especially in regard to the car following model and its ability to differentiate between congested and non-congested conditions.

To effectively develop alternative VSL operating strategies**,** the traffic breakdown and bottleneck sources must be identified so that the VSL can target the sources of congestion along the corridor. These bottleneck locations have been identified in Chapter 4, and must be confirmed to exist in the simulation model as well. The speed profiles from the calibrated simulation model over all 12 time periods are shown in Figures 6-4 through 6-15. From the figures it is clear that a major bottleneck forms during Time Period 2 (7:15 – 7:30 AM) directly after the SR-408 (WB) on-ramp. Congestion does not dissipate until Time Period 10 (9:15 – 9:30 AM). The location and timing of this bottleneck are consistent with the results presented in Chapter 4, where this location was identified as the primary bottleneck. This merge area experiences congestion very frequently, primarily due to the high volume of vehicles merging from SR-408 WB onto an already near capacity mainline flow. This causes congestion which spreads several miles upstream over the course of 2 hours.

A secondary bottleneck develops upstream at the Kaley St. off-ramp during Time Period 4 (7:45 – 8:00 AM). This is a weaving segment with a high volume of traffic exiting towards Kaley St., with queues developing on the off-ramp. The reduced speeds at this location appear to be amplified by the traffic backing up from the downstream SR-408 bottleneck. It is not clear to what degree this would be a bottleneck if the downstream bottleneck was removed, therefore in our analysis we treat this as a secondary bottleneck.

The third area of potential congestion is around the Maitland Blvd. Eastbound and Westbound off-ramps. High demands for both of these off ramps result in long queues in the simulation. This potential bottleneck was not identified in Chapter 4, but will be considered as a potential bottleneck in the analysis.

These three locations are the focus of the VSL-related operational improvements. The next section presents different scenarios aimed to improve the effectiveness traffic operations through the use of VSL around these bottleneck areas.

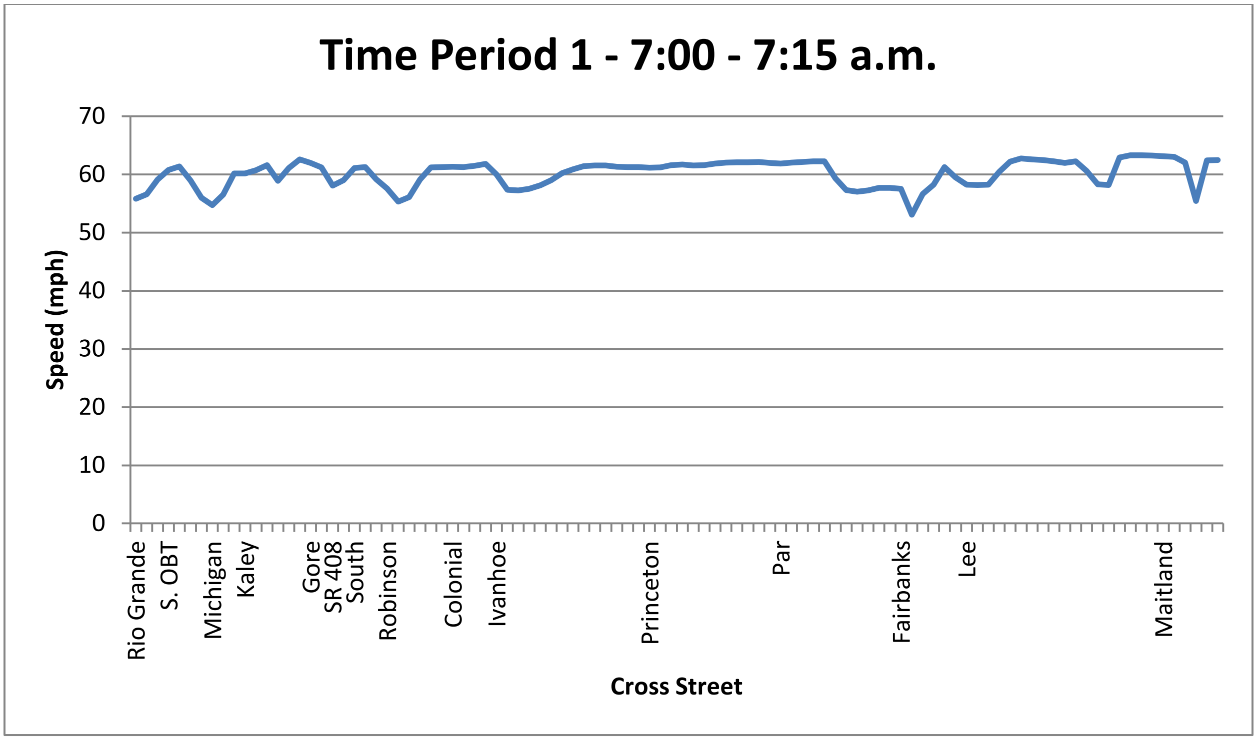


Figure 6.4 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 1)

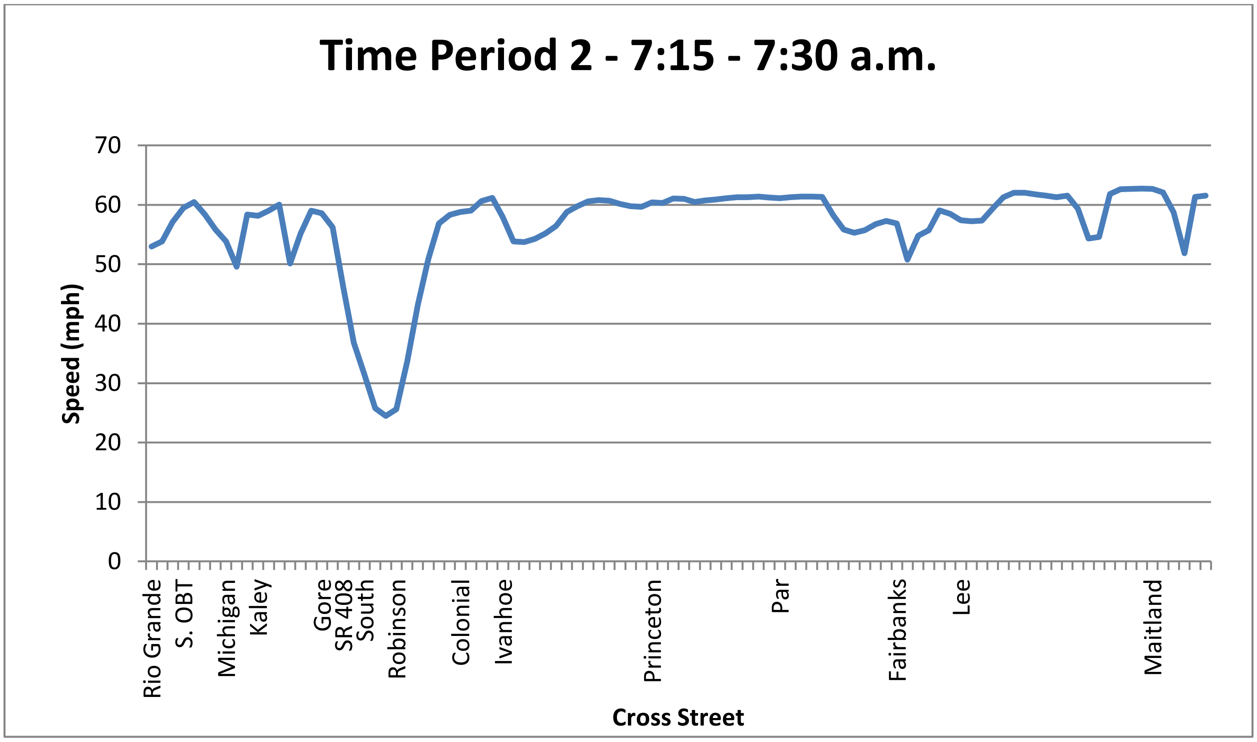


Figure 6.5 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 2)

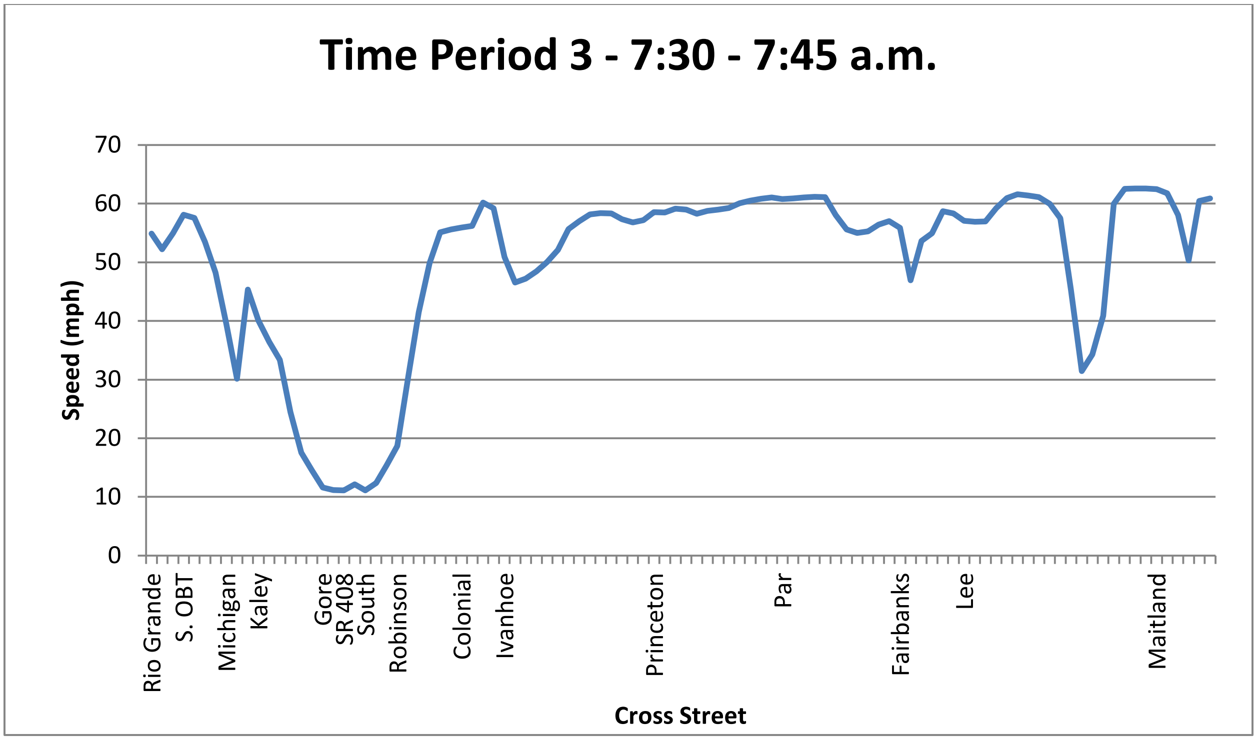


Figure 6.6 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 3)

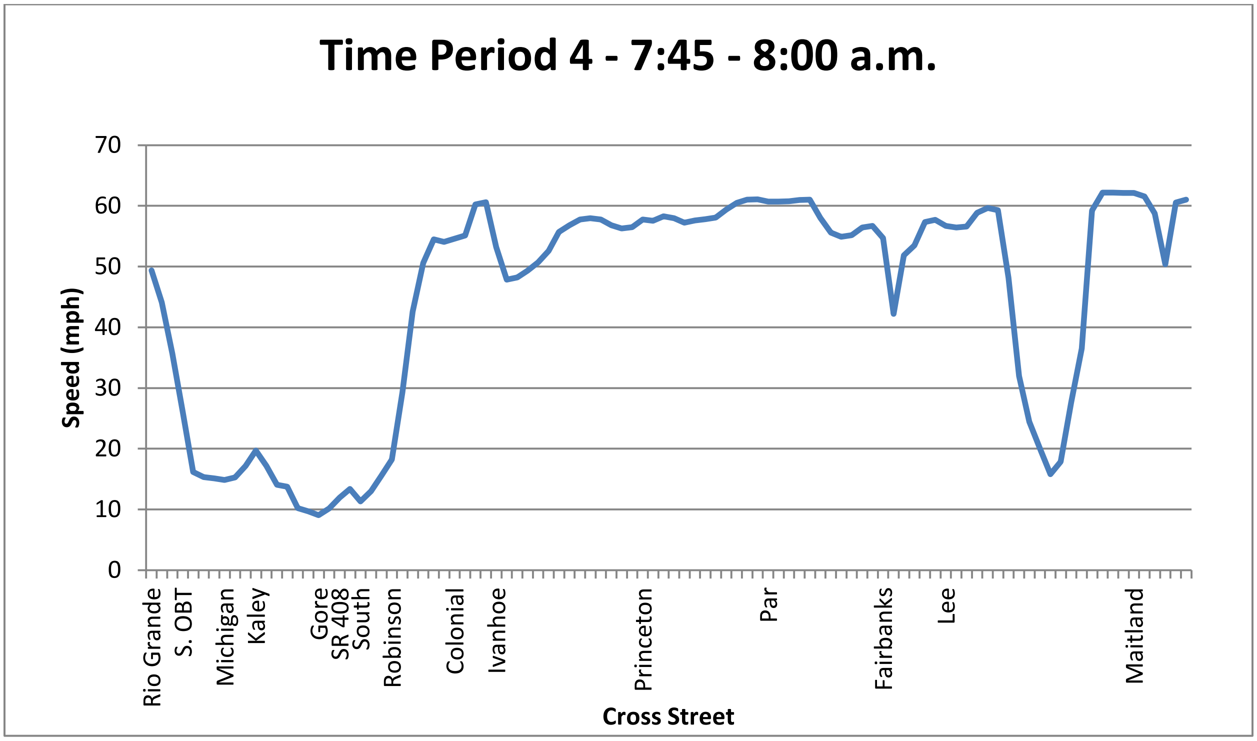


Figure 6.7 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 4)

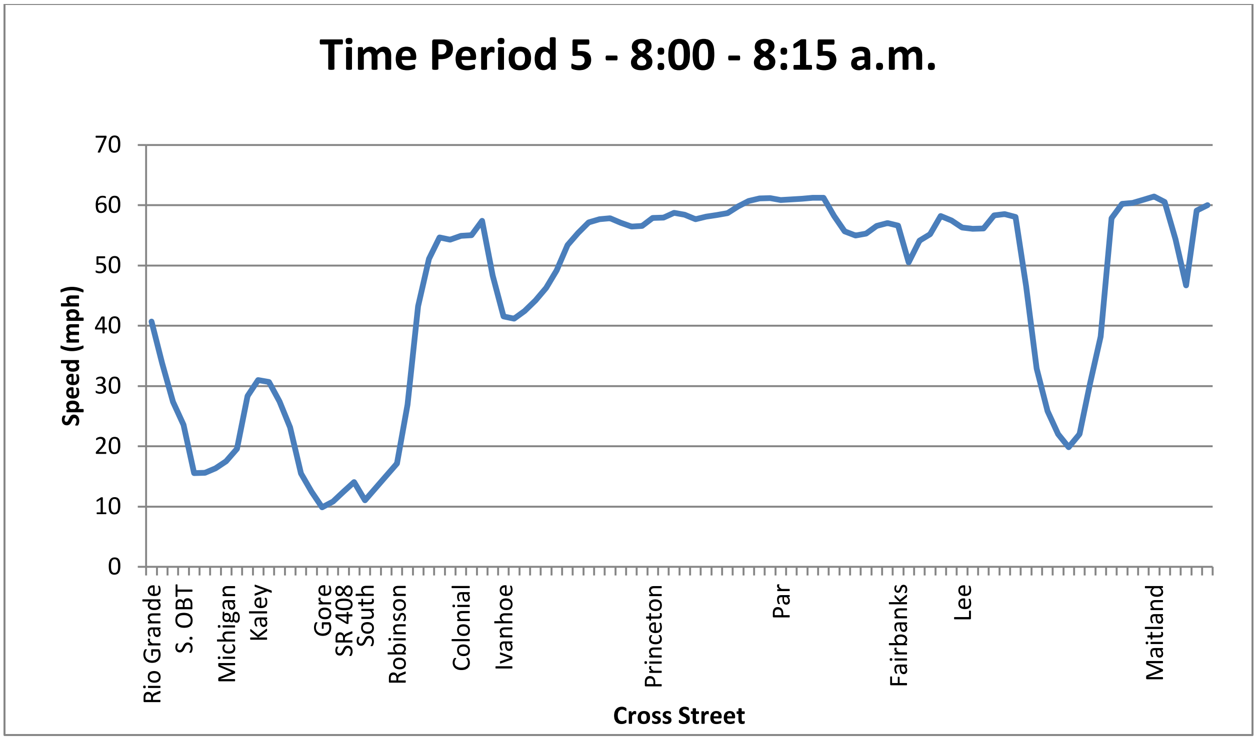


Figure 6.8 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 5)

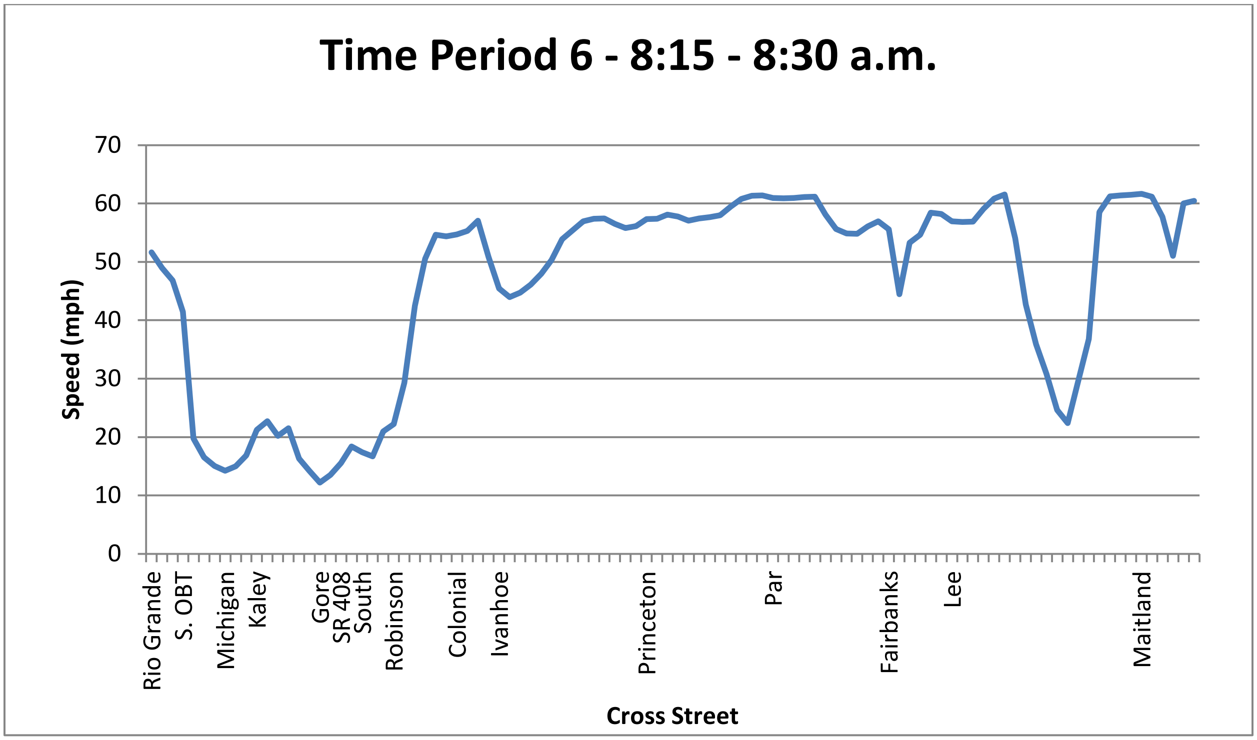


Figure 6.9 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 6)

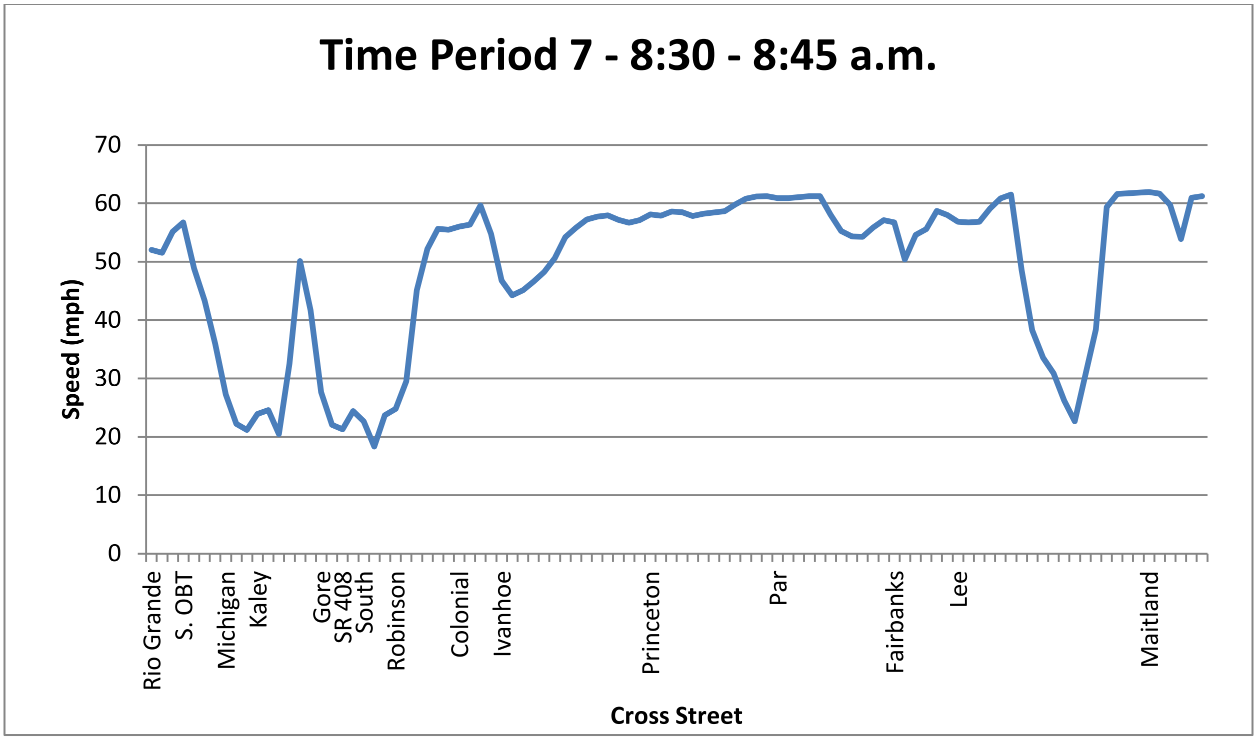


Figure 6.10 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 7)

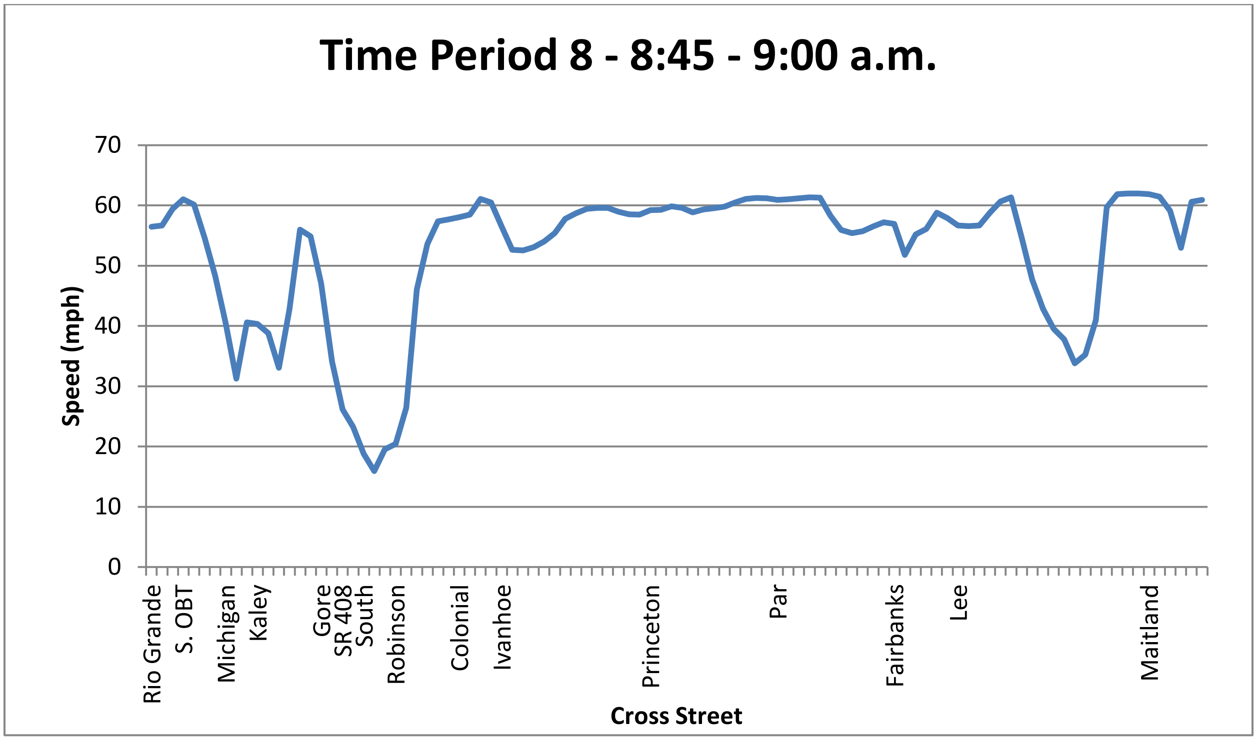


Figure 6.11 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 8)

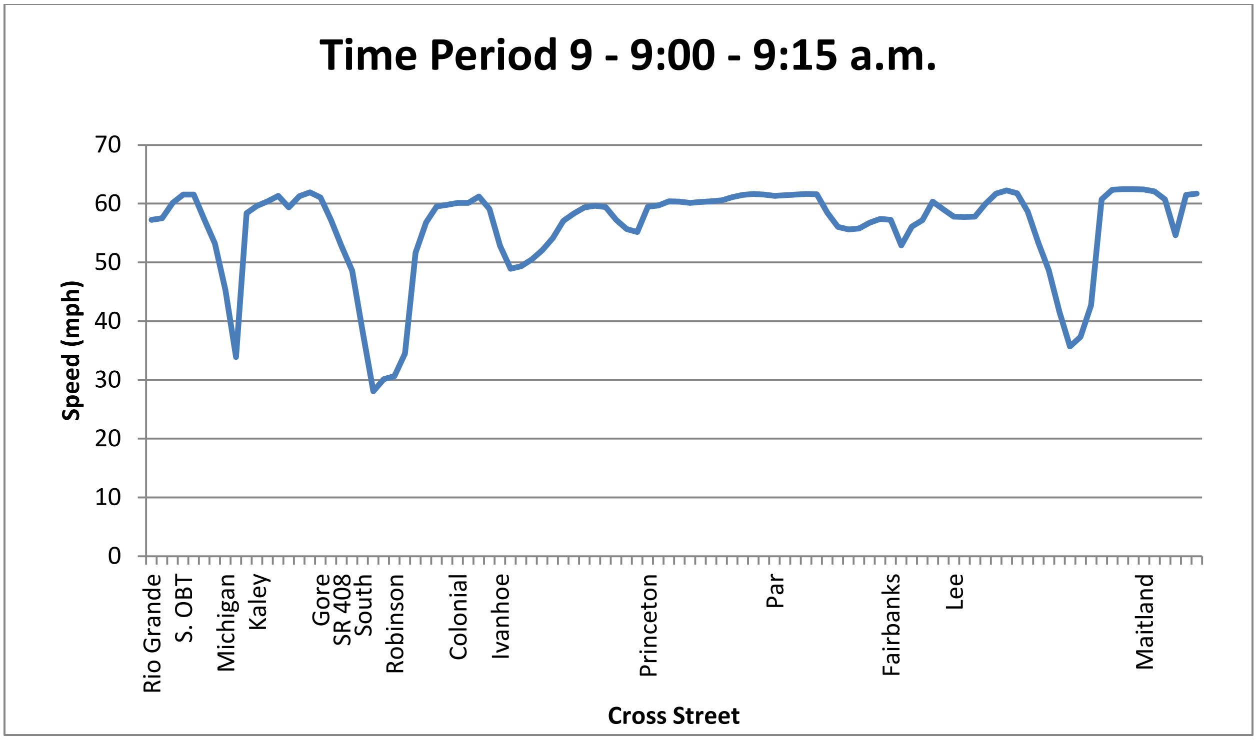


Figure 6.12 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 9)

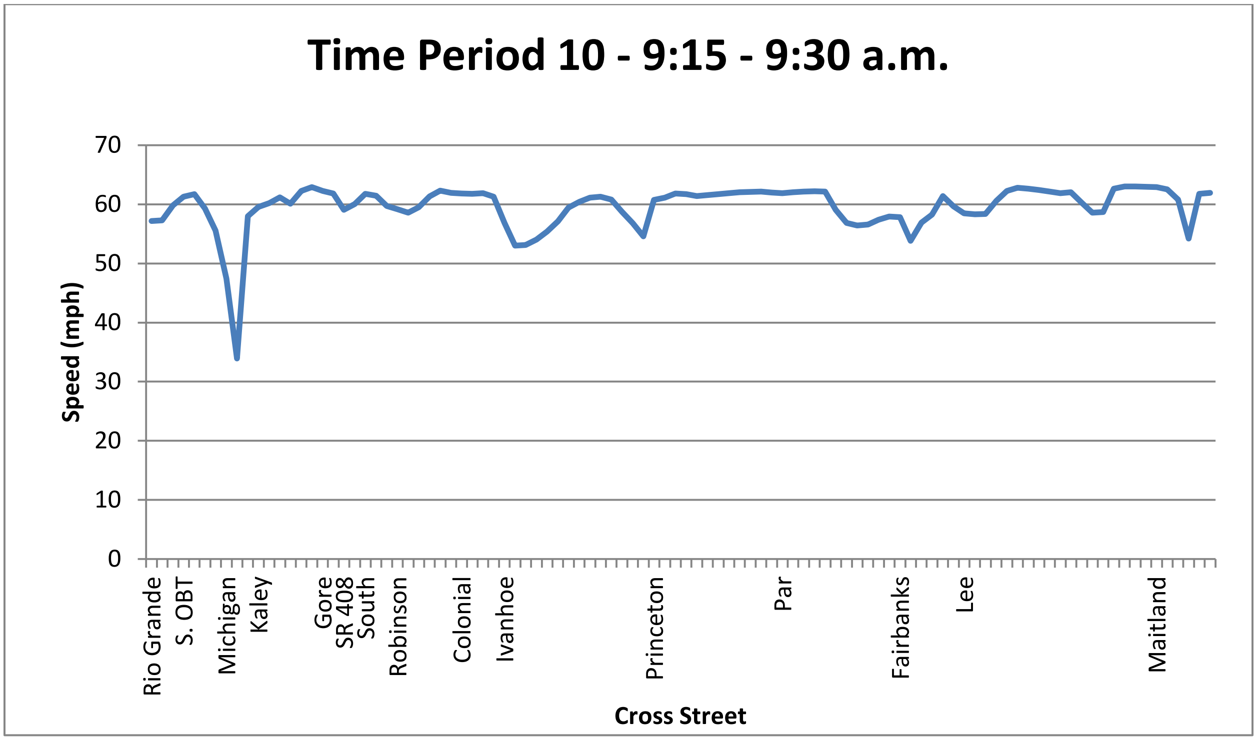


Figure 6.13 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 10)

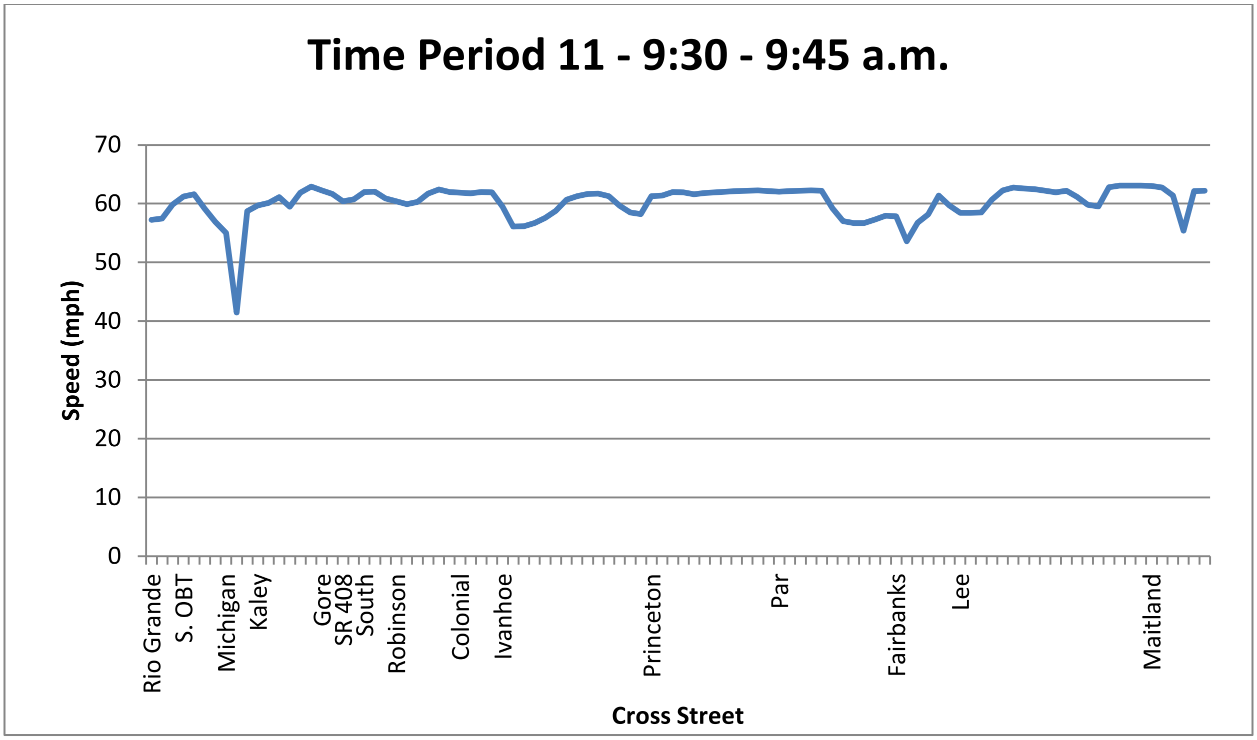


Figure 6.14 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 11)

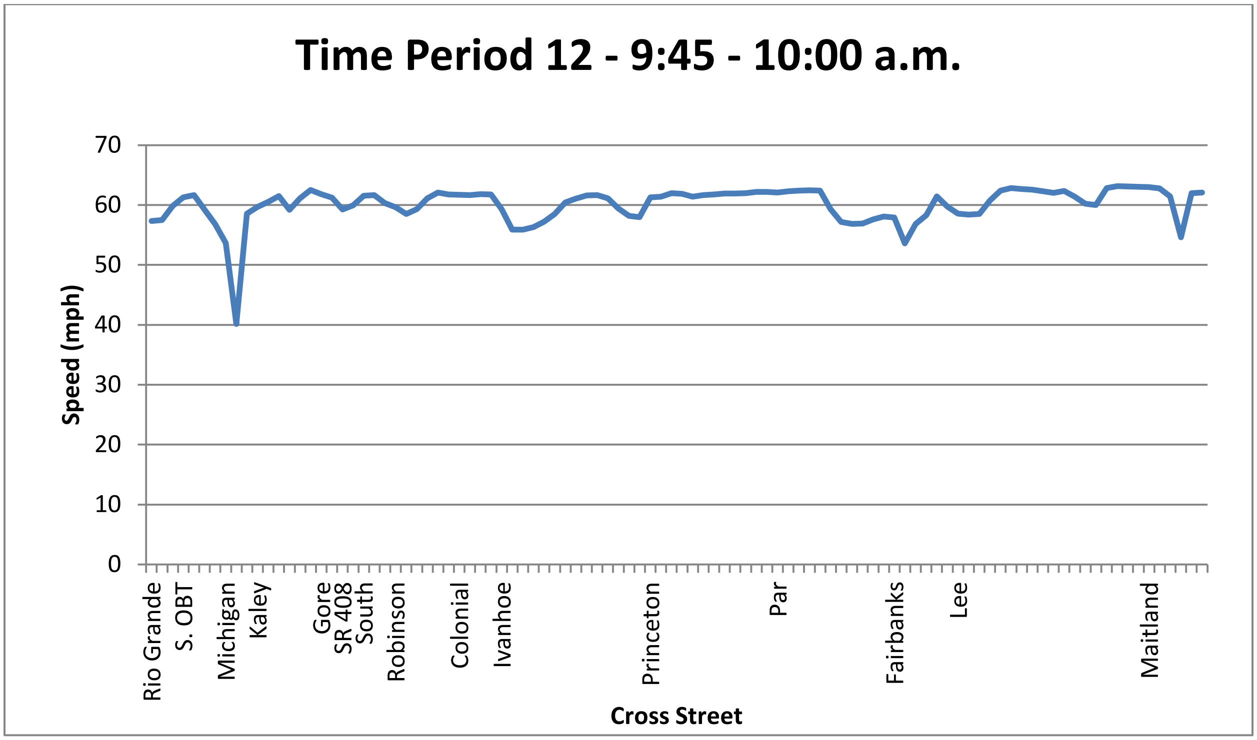


Figure 6.15 Speed profile for calibrated I-4 CORSIM simulation model (Time Period 12)

6.3 Simulation-Based Alternative Scenarios

Currently the VSL algorithm operating along I-4 is based on average occupancy values. The literature review identified two additional operating algorithms which could be tested. Therefore the algorithms selected for testing were occupancy-based, volume-based, and combined flow/occupancy/speed algorithm. These represent the major types of algorithms that have been tested and implemented around the world to-date.

The algorithm based on occupancy has two sets of threshold values, one for the decreasing of speed limits and one for the increasing of speed limits. The VSL sign is linked to downstream detectors, and the average occupancy is calculated for all lanes. The traffic is classified as either free-flow, light congestion, or heavy congestion. If the occupancy crosses a pre-specified threshold, the speed limit is decreased by an increment of ten miles per hour. Similarly the speed limit may increase back to its previous value but not more than 10 mph at a time. The threshold scenarios tested in this research (in addition to those currently implemented along the I-4 corridor) were generated based on findings from NCHRP Report 3-87 (Elefteriadou et al. 2009). That report studied occupancy values as a function of the probability of breakdown at merge junctions. The three threshold scenarios tested are shown in Table 6.2, Table 6.3, and Table 6.4.

Table 6.2 Occupancy thresholds for displayed speed limits currently used on I-4 (Scenario 1)

Traffic Category	**Occupancy for decreasing speed limit (%)**	**Occupancy for increasing speed limit (%)**	**Speed limit (mph)**
Free flow	< 16	< 12	50
Light congestion	16 - 28	12 - 25	40
Heavy congestion	> 28	>25	30

Table 6.3 Occupancy thresholds for displayed speed limits (Scenario 2)

Traffic category	**Occupancy for decreasing speed limit (%)**	**Occupancy for increasing speed limit (%)**	**Speed limit (mph)**
Free flow	< 10	< 8	50
Light congestion	10 - 25	8 - 22	40
Heavy congestion	> 25	>22	30

Table 6.4 Occupancy thresholds for displayed speed limits (Scenario 3)

Traffic category	**Occupancy for decreasing speed limit (%)**	**Occupancy for increasing speed limit (%)**	**Speed limit (mph)**
Free flow	< 20%	< 17%	50
Light congestion	20 - 35%	17 - 32%	40
Heavy congestion	> 35%	>32%	30

The algorithm based on volumes also uses two threshold values; one for the decreasing of speed limits and one for the increasing of speed limits. The VSL sign is linked to a downstream detector location, and average volume is computed in vehicles per hour per lane. When the volume drops below a specified threshold, the speed limit is decreased accordingly. To return to the original speed the volume must cross a different threshold. The first set of threshold values were obtained from a study conducted on the M25 in England (Robinson, 2000), and are shown in Table 6.5. The other thresholds were obtained from speed flow diagrams in the 2010 Highway Capacity Manual (HCM, 2010), and are shown in Tables 6.6 and 6.7. The thresholds are obtained by locating the volume of traffic where speeds drop for a given speed, using the associated volume as the threshold point.

Table 6.5 Volume thresholds for displayed speed limits (Scenario 1)

Flow for decreasing speed limit (vphpl)	**Flow for increasing speed limit (vphpl)**	**Speed limit (mph)**
< 1650	-	50
> 1650	< 1450	40
> 2050	<1850	30

Table 6.6 Volume thresholds for displayed speed limits (Scenario 2)

Flow for decreasing speed limit (vphpl)	**Flow for increasing speed limit (vphpl)**	**Speed limit (mph)**
< 1450	-	50
> 1450	< 1250	40
> 1900	<1700	30

Table 6.7 Volume thresholds for displayed speed limits (Scenario 3)

Flow for decreasing speed limit (vphpl)	**Flow for increasing speed limit (vphpl)**	**Speed limit (mph)**
< 1800	-	50
> 1800	< 1700	40
> 2100	< 1900	30

The third algorithm is based on a logic tree that includes flow, occupancy, and average travel speed. The two selected threshold scenarios are shown in Figure 6.16 and Figure 6.17. The algorithm first takes into account flow data from a downstream loop detector. If the volume is less than or equal to 1650 vphpl, the next step is to consider occupancy. If occupancy is less than or equal to 10%, the maximum speed limit is posted. If the occupancy is greater than 10%, average speed determines which speed is displayed. Going back to the first step, if the volume is greater than 1650 vphpl, the logic skips straight to the average speed calculation. The speed to be displayed is then sent to the appropriate VSL sign. This algorithm is based on research conducted on a candidate VSL system in Toronto, Canada (Allaby, 2007).

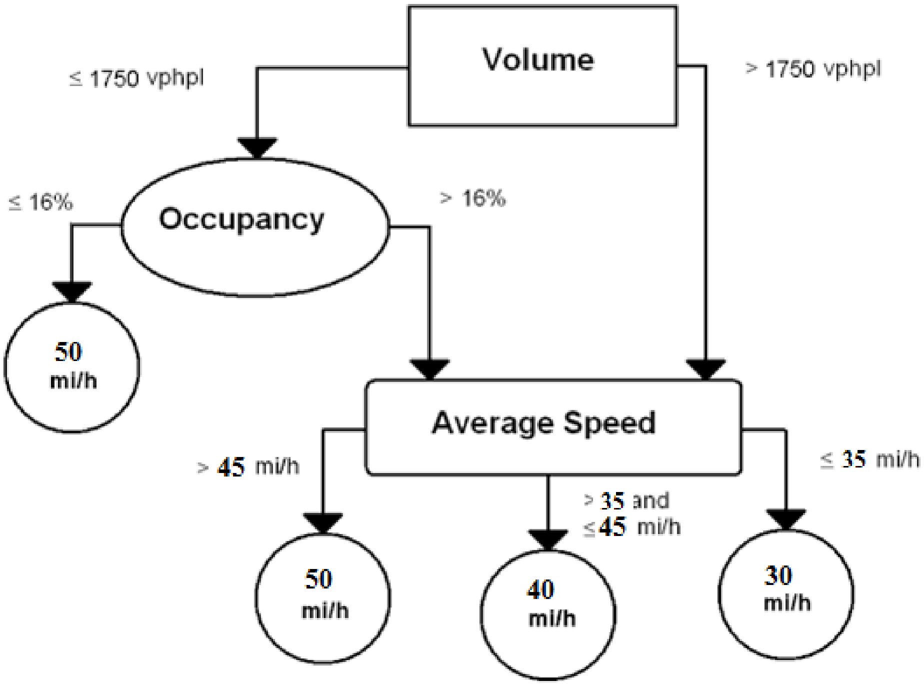


Figure 6.16 Decision tree logic for combined flow/occupancy/speed algorithm Scenario 1

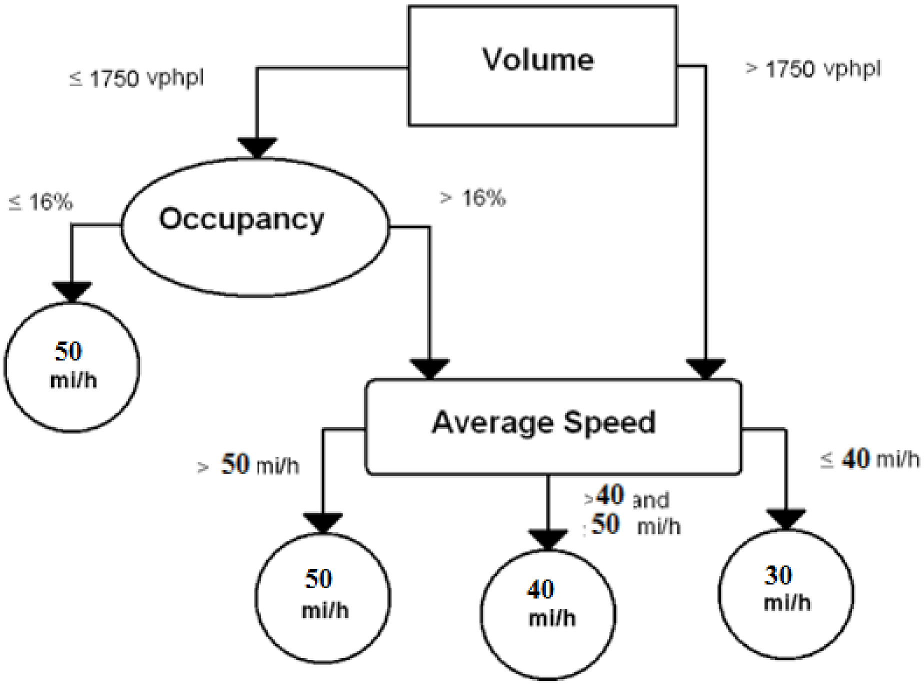


Figure 6.17 Decision tree logic for combined flow/occupancy/speed algorithm (Scenario 2)

In addition to testing different algorithms and thresholds, different sign and detector locations were tested for isolated bottleneck locations. The scenarios tested consider placing detectors at the bottleneck, including one VSL sign spaced one half mile upstream from the bottleneck, and placing two signs spaced one half mile apart.

Section 6.3.1 provides an assessment of the current I-4 VSL sign and detector arrangement using the different algorithms and thresholds described earlier. Section 6.3.2 provides the same analysis, but using the maximum value from a set of detectors instead of the average (as per the recommendations provided in Chapter 3). The remaining sections analyze each bottleneck individually, using the occupancy algorithm with different sign spacing, detector relationships, and thresholds.

6.3.1 Assessing Current Sign Configuration with Alternate Algorithms

The first set of scenarios used the existing sign configuration and detector relationship, while altering the algorithm and thresholds for VSL control. These scenarios were run identically as the calibrated file was, and the same output processing was performed. A scenario was also included with no VSL control to assess the operations without any VSL control.

These scenarios assumed driver compliance is equal to actual observed compliance levels in the field. In the simulation, when the speed limit is reduced by 10 mph, the desired free flow speed is only reduced by 3.41 mph. This is designed to replicate the actual reaction of drivers to the reduced speed limit sign. The network-wide total travel time and average speed for each scenario tested are shown in Table 6.8.

Table 6.8 Network Wide Travel Time and Speed for No-VSL and for the Existing VSL Configuration

Scenario	**Total Travel Time (hours)**	**Average Speed (mph)**
No VSL Control	4332	46.81
Existing Operations	4383	46.56
Occupancy Low Thresholds	4492	45.48
Occupancy High Thresholds	4362	46.57
Volume Low Thresholds	4494	45.38
Volume Middle Thresholds	4366	46.02
Volume High Thresholds	4378	46.46
Multiple Parameter 1	4436	45.99
Multiple Parameter 2	4392	46.41

The results show little to no change between the existing operations and the scenarios tested. The no-VSL scenario resulted in slightly better average speed. The thresholds seem to make a significant difference in operations (for example, for the occupancy algorithm the “low” thresholds reduce speed by approximately 1 mph).

In addition to the travel time and average speed, we obtained throughout values at the downstream end of the VSL zone throughout the simulation. The throughput over all 12 time periods is shown in Table 6.9. Again, there are no noticeable differences in the throughput at this downstream location.

Table 6.9 Throughput (in vehicles) at the downstream end of the VSL zone over each of the 12 time periods

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
No Control	549	745	805	744	971	897	841	842	729	700	693	651
Existing Operations	551	753	801	739	932	892	833	876	749	684	685	653
Occupancy Low Thresholds	546	740	803	726	954	898	830	867	753	692	688	656
Occupancy High Thresholds	551	745	794	762	932	891	837	850	748	699	691	662
Volume Low Thresholds	536	735	814	745	924	906	826	866	755	703	694	657
Volume Middle Thresholds	538	742	795	758	946	878	819	832	726	694	654	634
Volume High Thresholds	553	738	808	757	972	884	843	850	733	697	685	648
Multiple Parameter 1	540	758	798	753	933	894	849	834	750	709	690	646
Multiple Parameter 2	550	751	799	758	945	900	836	869	745	688	683	651

6.3.2 Current Sign Configuration with Alternate Algorithms and Max of Detector Output

The current VSL sign/detector relationship links a given VSL sign to two or three downstream detectors, and averages the occupancy values from these detectors. From an analysis performed in Chapter 3 it was proposed that by averaging between two or more detectors the occupancy value is being diluted; one detector may be reading very high occupancy values, while the other may be reading lower values. The resulting average occupancy is too low to trigger a speed limit reduction. Testing was performed to evaluate conditions if the “worst detector” output was used in the VSL algorithm. This was implemented for the occupancy, volume, and multiple parameter based algorithms. The scenarios tested used the highest occupancy and flow readings and the lowest speed readings within the three identified algorithms and for the associated threshold values. Again, these scenarios assumed driver compliance is equal to actual observed compliance levels in the field. In the simulation this compliance is assumed to be 34.1%. When the speed limit is reduced by 10 mph, the desired free flow speed is only reduced by 3.41 mph. The results of these simulation experiments are shown in Table 6.10.

Table 6.10 Simulation results using maximum/minimum detector readouts

Scenario	**Total Travel Time (hours)**	**Average Speed (mph)**
No VSL Control	4332	46.81
Existing Operations	4383	46.56
Occupancy Middle Max	4402	46.28
Occupancy Low Thresholds Max	4464	45.56
Occupancy High Thresholds Max	4449	46.16
Volume Low Thresholds Max	4607	44.45
Volume Middle Thresholds Max	4524	45.17
Volume High Thresholds Max	4482	45.51
Multiple Parameter 1 Max	4283	47.25
Multiple Parameter 2 Max	4356	46.62

Most of the scenarios show little to no improvement over the existing operations; however the multiple parameter algorithm shows an improvement over existing operations, as well as over the no-VSL scenario. Therefore, changing the detector configuration can increase average speed for the entire corridor. The throughput displayed no improvement over the 12 time periods. For this particular scenario, we also plotted the speeds vs. distance for each time period (Figure 6.18). As shown in Figure 6.18, there is a relatively small improvement in the speeds during congested periods.

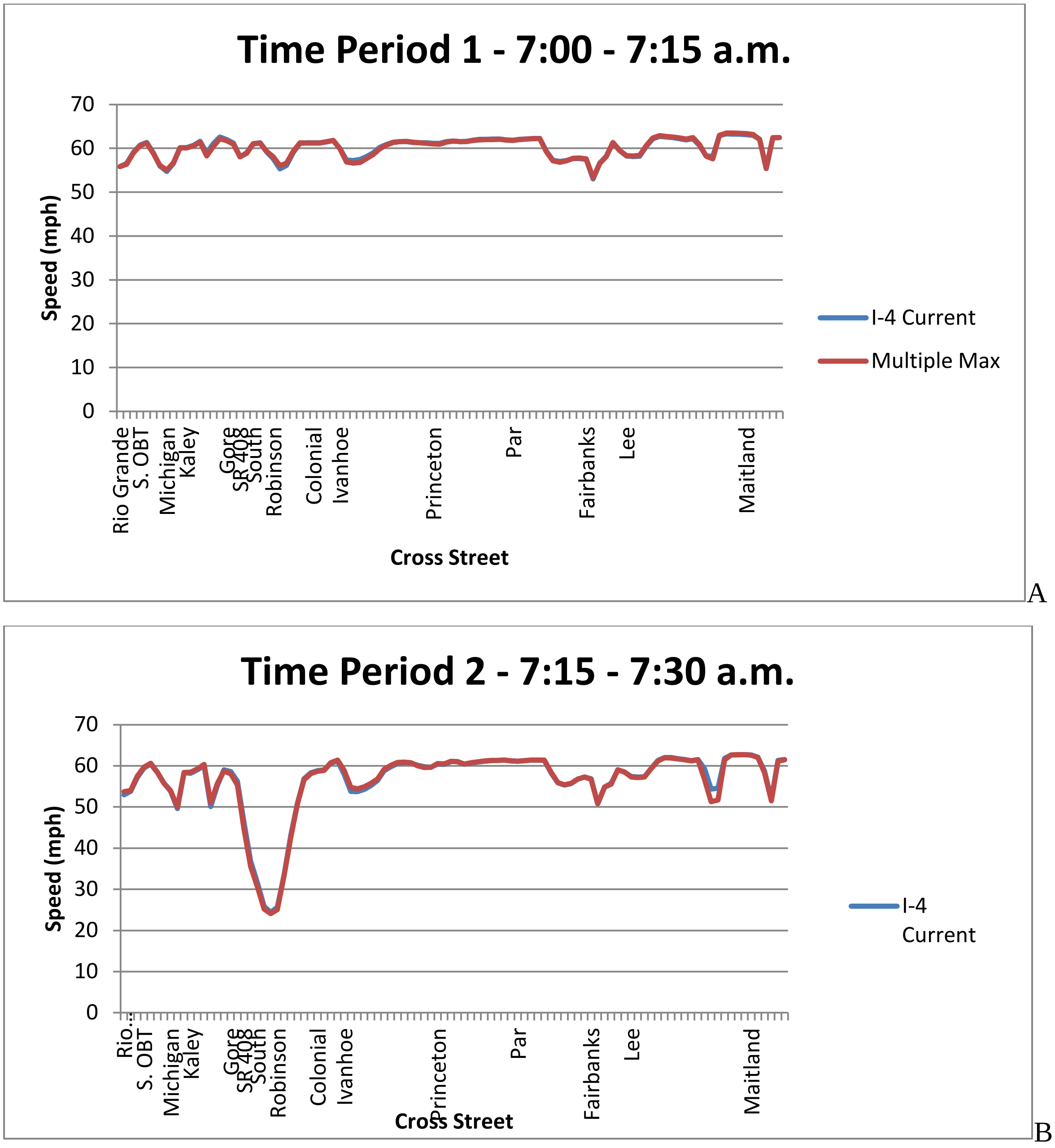
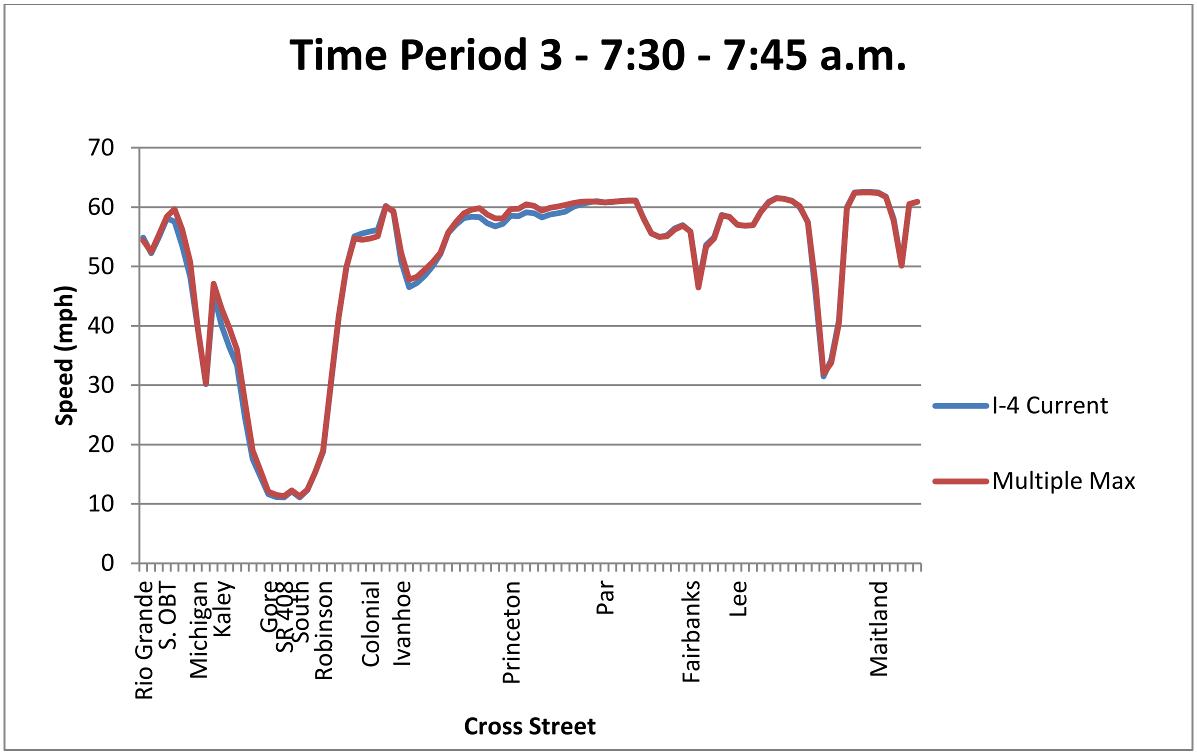


Figure 6.18 Speed versus distance plots for the Multiple Parameter 1 Max scenario: A) time period 1; B) time period 2; C) time period 3; D) time period 4; E) time period 5; F) time period 6; G) time period 7; H) time period 8; I) time period 9; J) time period 10; K) time period 11; L) time period 12



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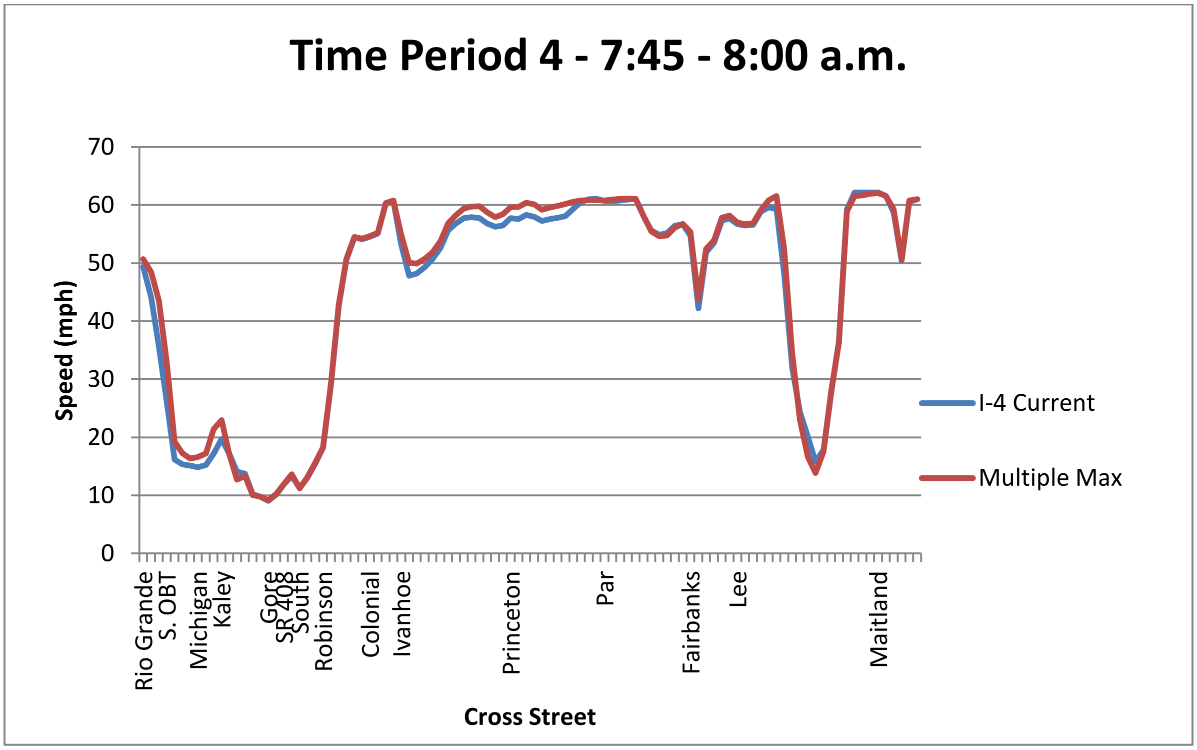

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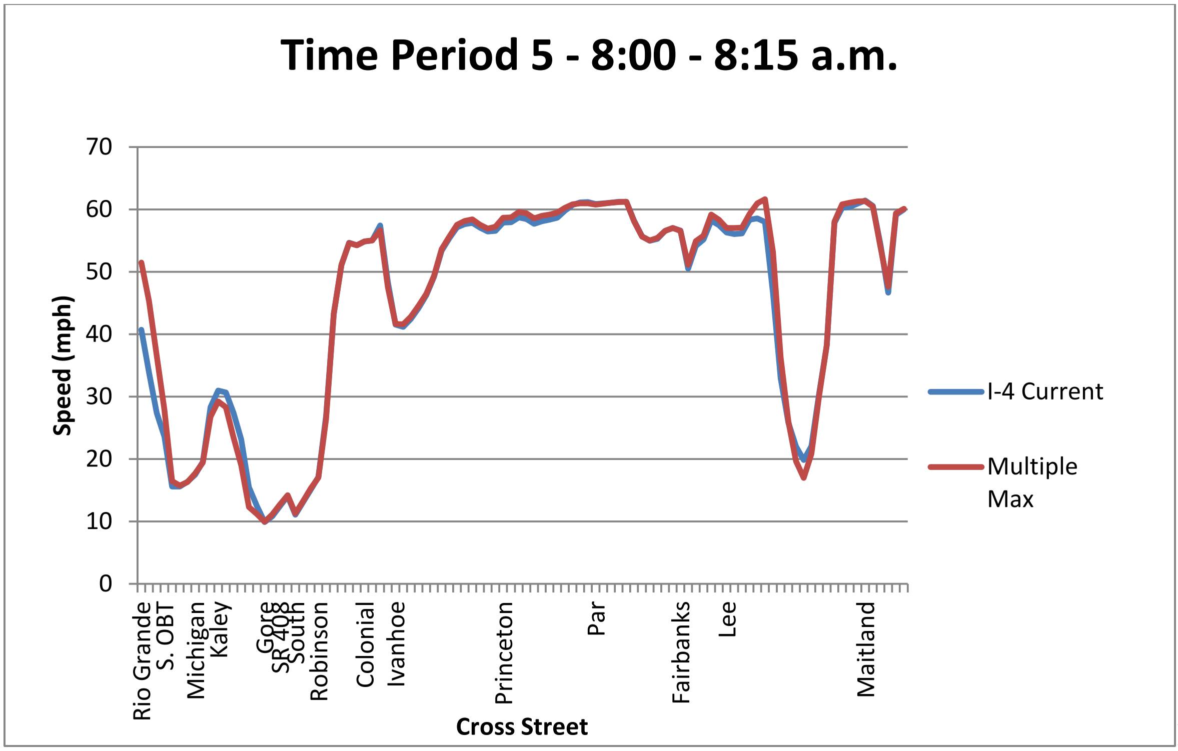
Figure 6.18 Speed versus distance plots for the Multiple Parameter Max 1 scenario A) time 1eriod 1 B) time period 2 C) time period 3 D) time period 4 E) time period 5 F) time period 6 G) time period 7 H) time period 8 I) time period 9 J) time period 10 K) time period 11 L)time period 12 (continued)



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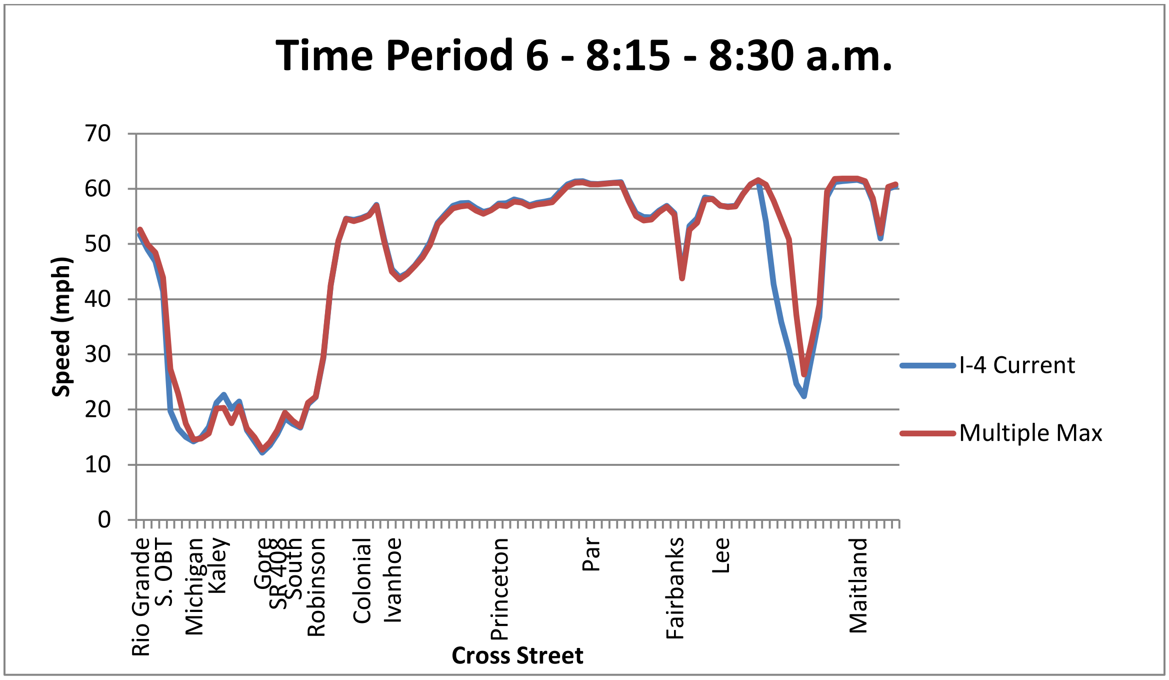

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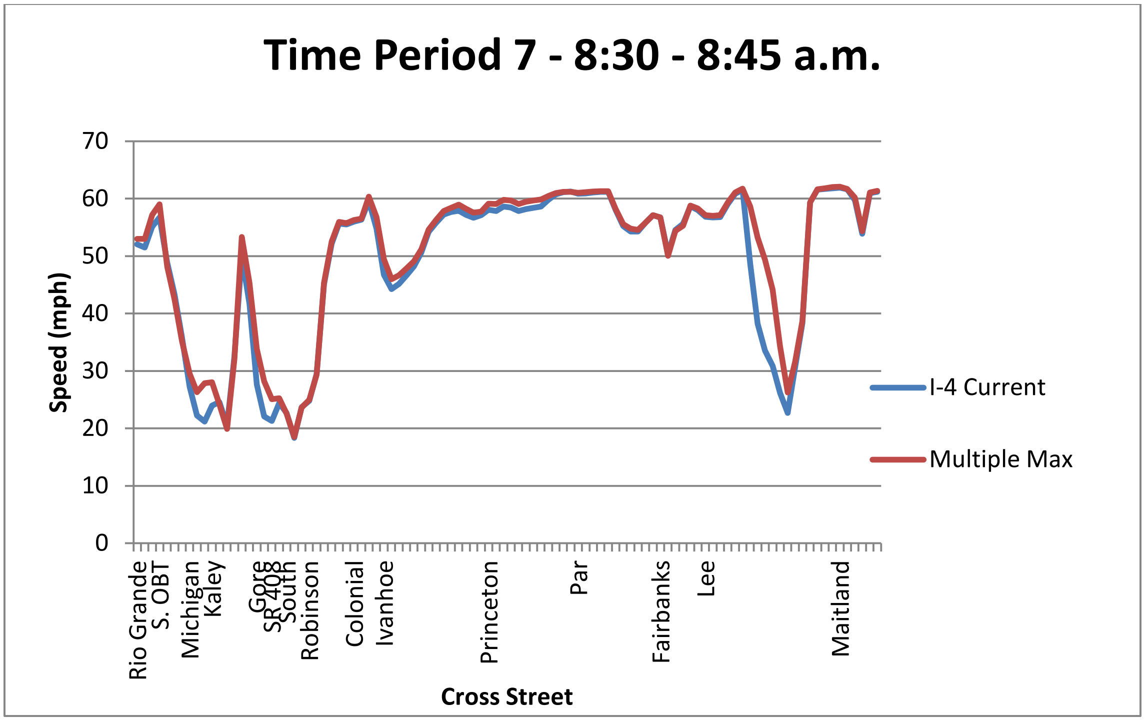
Figure 6.18 Speed versus distance plots for the Multiple Parameter Max 1 scenario A) time 1eriod 1 B) time period 2 C) time period 3 D) time period 4 E) time period 5 F) time period 6 G) time period 7 H) time period 8 I) time period 9 J) time period 10 K) time period 11 L)time period 12 (continued)



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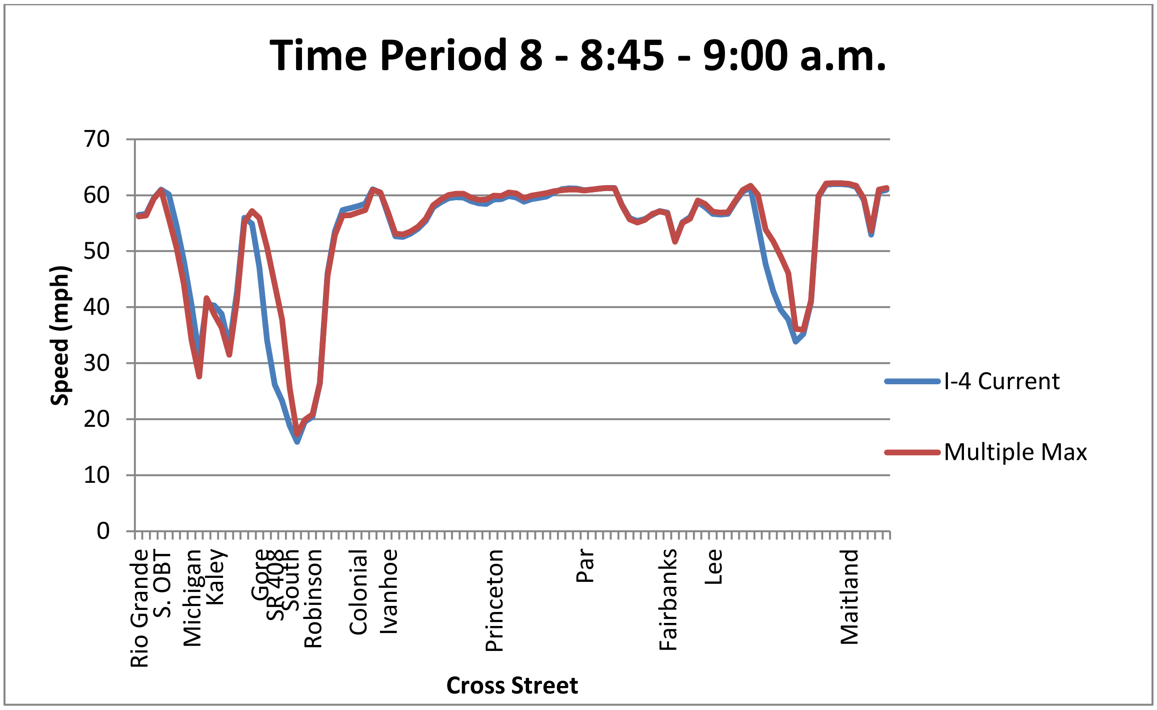

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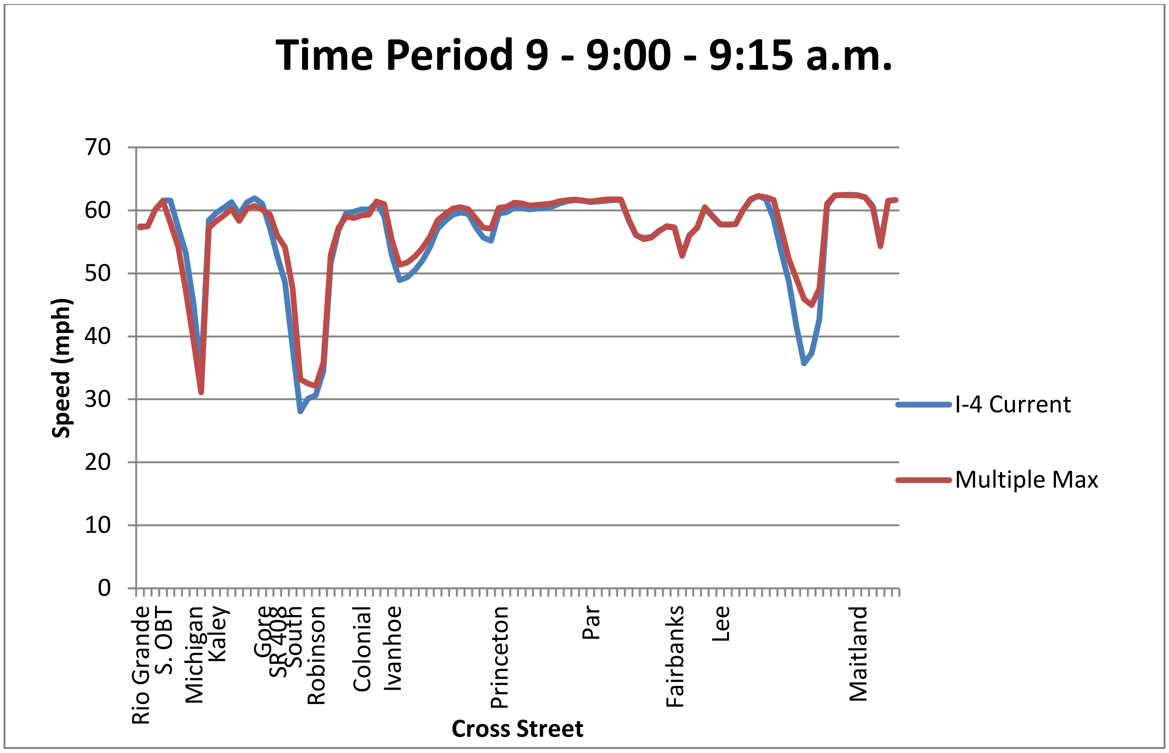
Figure 6.18 Speed versus distance plots for the Multiple Parameter Max 1 scenario A) time 1eriod 1 B) time period 2 C) time period 3 D) time period 4 E) time period 5 F) time period 6 G) time period 7 H) time period 8 I) time period 9 J) time period 10 K) time period 11 L)time period 12 (continued)



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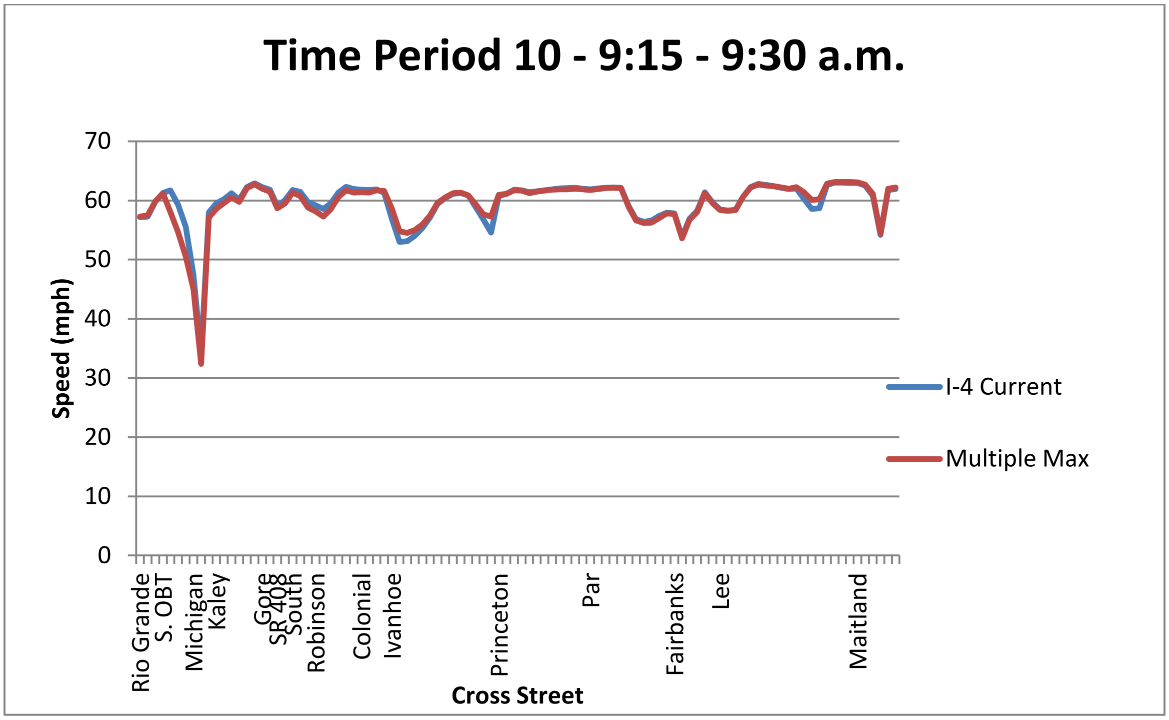

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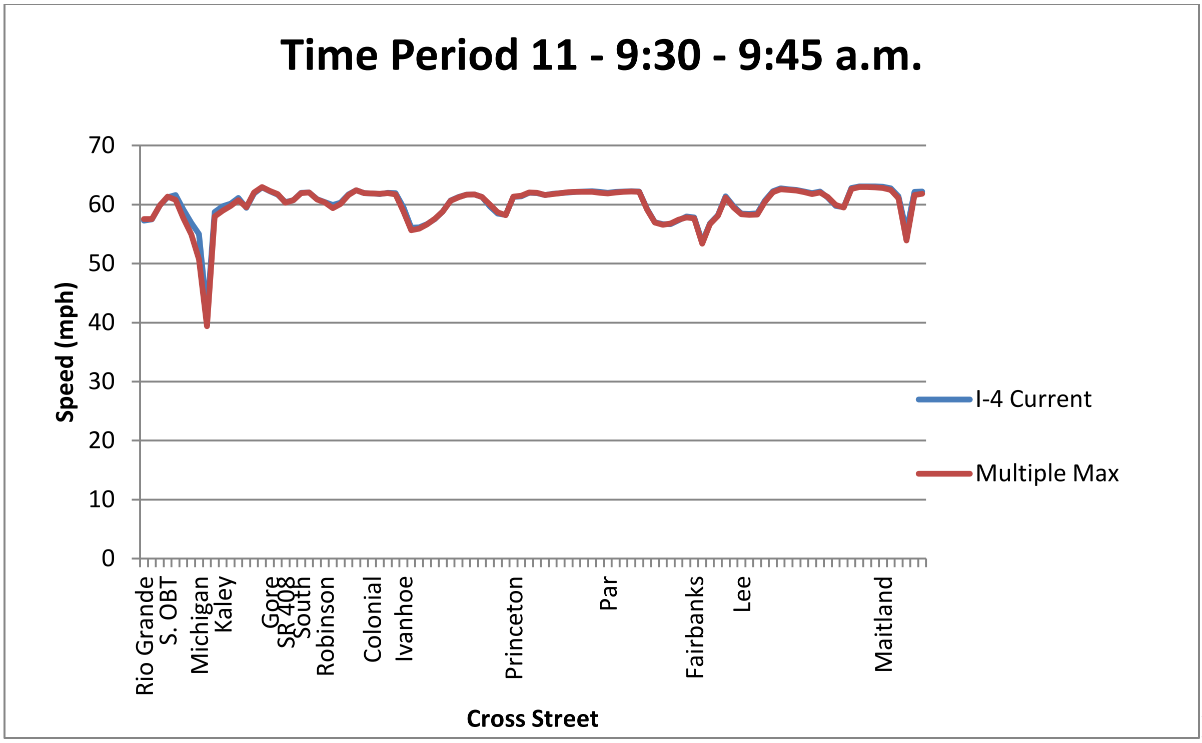
Figure 6.18 Speed versus distance plots for the Multiple Parameter Max 1 scenario A) time 1eriod 1 B) time period 2 C) time period 3 D) time period 4 E) time period 5 F) time period 6 G) time period 7 H) time period 8 I) time period 9 J) time period 10 K) time period 11 L)time period 12 (continued)



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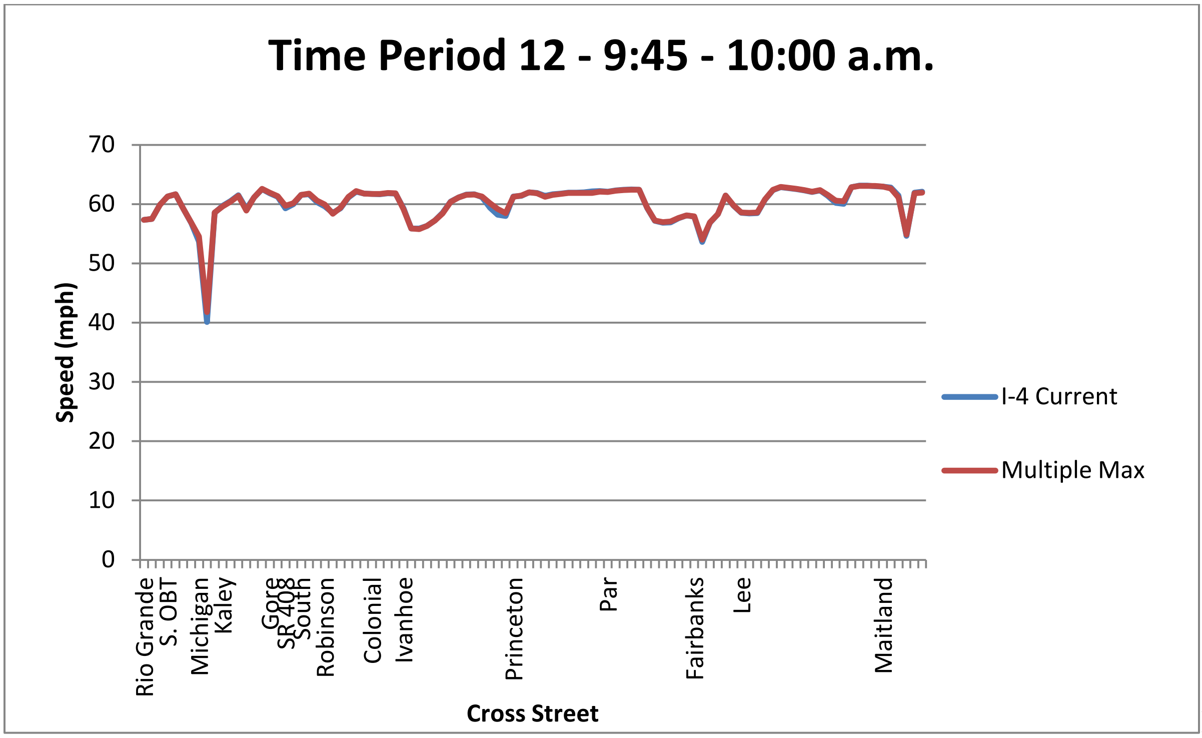

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Figure 6.18 Speed versus distance plots for the Multiple Parameter Max 1 scenario A) time 1eriod 1 B) time period 2 C) time period 3 D) time period 4 E) time period 5 F) time period 6 G) time period 7 H) time period 8 I) time period 9 J) time period 10 K) time period 11 L)time period 12 (continued)

The next set of scenarios examines each bottleneck individually to determine whether specific types of bottlenecks function best with a particular VSL algorithm, as well as with different detector and sign placement. In theory, by placing a VSL sign upstream of the bottleneck, speeds will be reduced, and this reduction in speed will result in a reduction in flow, which in effect reduces the speed the shockwave. By delaying the onset of congestion, improvements in performance should be seen through this section.

6.3.3 Isolating VSL Control for the Upstream Secondary Bottleneck

The first bottleneck analyzed is the weaving section between the on-ramp from Michigan St. and the off-ramp to Kaley St. Figure 6.19 shows the bottleneck sketch and the surrounding area. As discussed earlier, this is a secondary bottleneck and traffic backs up from downstream and spills back into the weaving segment. Therefore the impact of the VSL system may be different on those types of bottlenecks, as congestion originates somewhere downstream.

Two different sign spacing scenarios were tested at this bottleneck location: the first scenario has one sign spaced approximately one half mile from the bottleneck source, while the second scenario has two signs spaced approximately one half mile apart. Directly after the weaving segment, the speed limit is assumed to operate as a static sign displaying 50 mph. These different sign scenarios are illustrated in Figure 6.20. The algorithm controlling the VSL operations is the current occupancy-based algorithm used on I-4. The results from the simulations are presented in Table 6.11. In the table the “local average” refers to an area containing the bottleneck as well as a total of 1.5 miles of roadway surrounding the bottleneck.

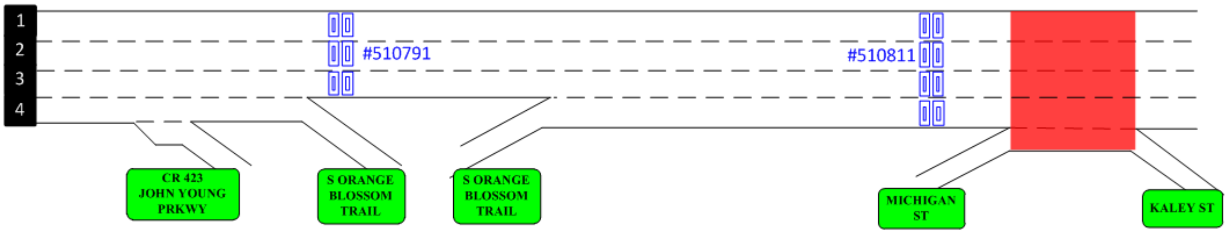

Figure 6.19 Location and sketch of the first downstream bottleneck

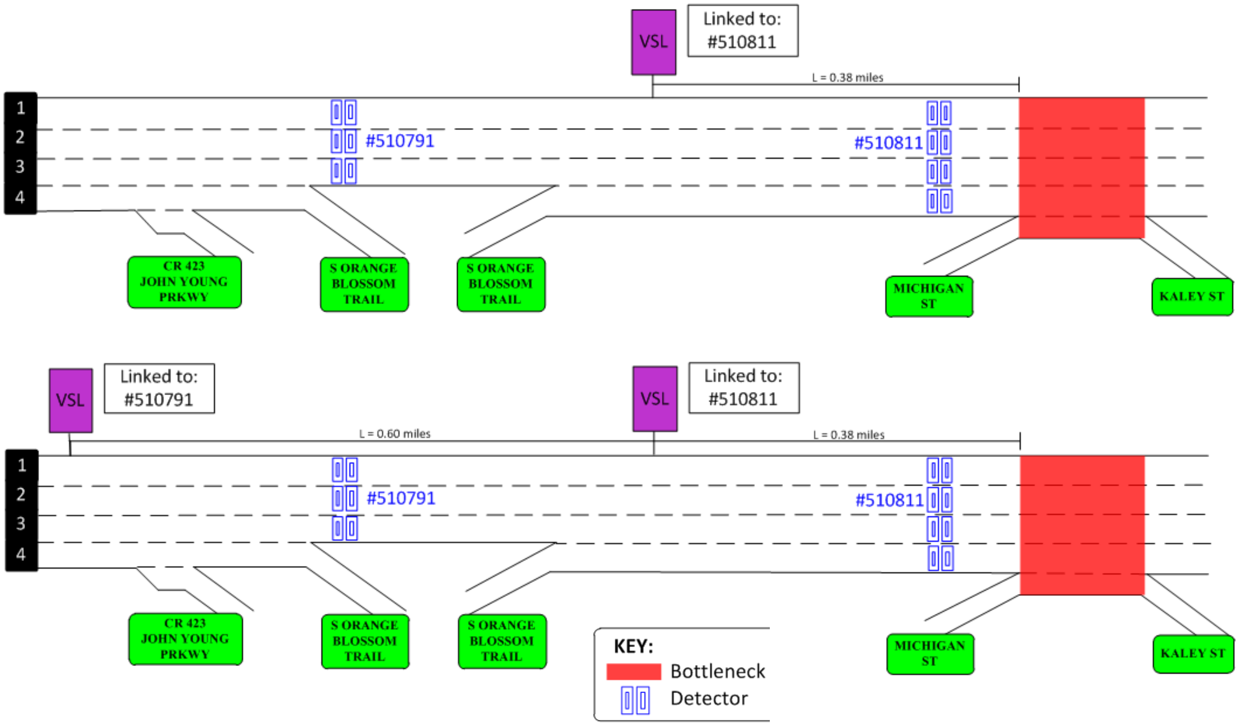

Figure 6.20 VSL sign placement scenarios a) 1 sign placed one half mile upstream of bottleneck; b) 2 signs spaced one half mile apart

Table 6.11 Simulation results using different sign locations at upstream bottleneck

Scenario	**Network Total Travel Time (hours)**	**Network Average Speed (mph)**	**Local Total Travel Time (min)**	**Local Average Speed (mph)**
No VSL Control	4332	46.81	23390	41.34
Existing Operations	4383	46.56	22985	42.01
Occupancy 1 Sign	4412	46.27	23699	42.07
Occupancy 2 Signs	4448	45.96	23685	41.41

The results again show no improvement over the existing operations in terms of average speed or travel time for the network. However, operations with the VSL appear to be better than without the VSL for all scenarios. The best scenario in this case seems to be the occupancy based one with 1 sign. It is interesting to note that the average speed at the bottleneck increases, while the network wide speed decreases for this particular scenario. We also examined the throughput but we did not identify any noticeable improvement over the 12 time periods for any of these scenarios.

6.3.4 Isolating VSL Control for the Main Bottleneck

The main bottleneck is located along the merging area just after the on-ramp from SR. 408 (WB). This is a high volume merging area which causes spillback for several miles. This is the source of congestion impacting the weaving area located upstream and analyzed in the previous set of scenarios. Figure 6.21 shows the bottleneck and the surrounding roadway geometry.
In the current I-4 VSL operation, the closest sign to this bottleneck is located 1.4 miles upstream, and is linked to detectors upstream and downstream from the bottleneck. The scenarios tested in this section are designed to test various sign spacing scenarios and to include a detector directly at the bottleneck.

Two different sign spacing scenarios were tested at this bottleneck location: the first one has one sign located approximately one half mile upstream from the bottleneck, and the second one has two signs spaced approximately one half mile apart. Directly after the off-ramp to Amelia St, the speed limit is assumed to operate as a static sign displaying 50 mph. These different sign scenarios are illustrated in Figure 6.22. The algorithm controlling the VSL operations is the current occupancy-based algorithm used on I-4. However, a new detector was placed at the source of congestion to more rapidly capture potential traffic breakdowns. The results from the simulations are presented in Table 6.12.

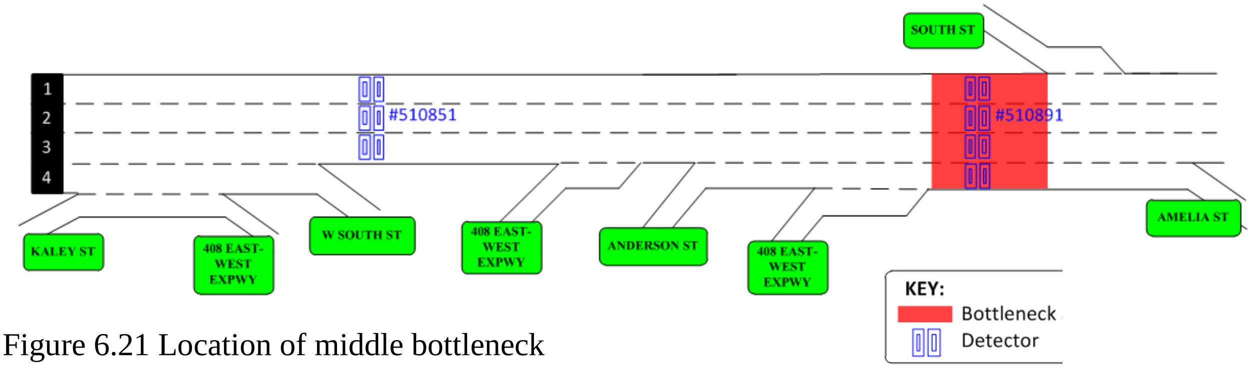

Figure 6.21 Location of middle bottleneck

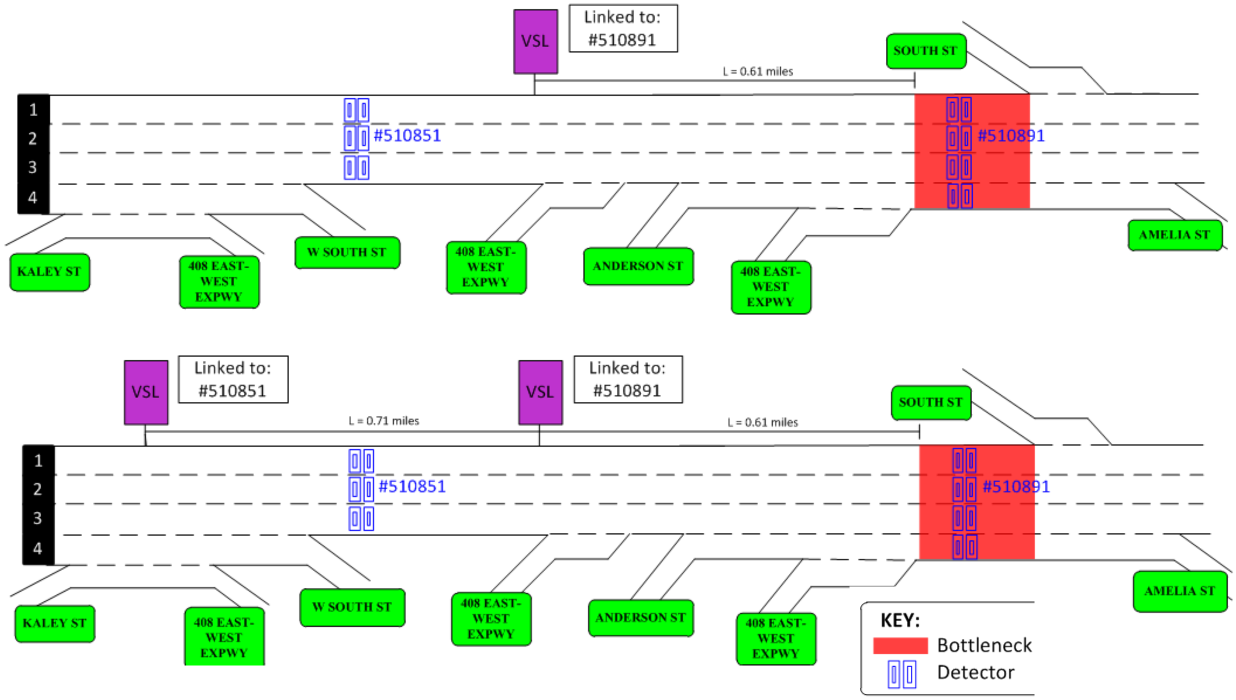

Figure 6.22 VSL sign placement scenarios a) 1 sign spaced one half mile from bottleneck; b) 2 signs spaced one half mile apart

Table 6.12 Simulation results using different sign locations at the main bottleneck

Scenario	**Total Travel Time (hours)**	**Average Speed (mph)**	**Local Total Travel Time (min)**	**Local Average Speed (mph)**
No VSL Control	4332	46.81	61649	39.47
Existing Operations	4383	46.56	63323	38.75
Occupancy 1 Sign	4446	45.94	63330	38.69
Occupancy 2 Signs	4397	46.39	63508	38.81

For this bottleneck, the results show no improvement over the existing operations in terms of average speed or travel time, and the no-VSL scenario shows slightly higher speeds for the network and for the bottleneck area. Also, the throughput displayed no noticeable improvement over the 12 time periods.

6.3.5 Isolating VSL Control for the Downstream Bottleneck

The downstream bottleneck occurs at the off-ramps toward Maitland Blvd. This bottleneck has not been consistently identified in the field, but shows potential for breakdown based on the simulation model. The high volume of exiting traffic at this location can create off-ramp queues that spill back into the freeway. Figure 6.23 provides a sketch of the bottleneck and surrounding area.

The same two sign spacing scenarios were tested at this bottleneck location, as those tested at the other two bottlenecks (shown in Figure 6.24). Directly after the off-ramps to Maitland Blvd., the speed limit is assumed to operate as a static sign displaying 50 mph. The algorithm controlling the VSL operations is the current occupancy-based algorithm used on I-4. However, a new detector was placed at the bottleneck, to be able to react faster to potential traffic breakdowns. The results from the simulations are presented in Table 6.8.

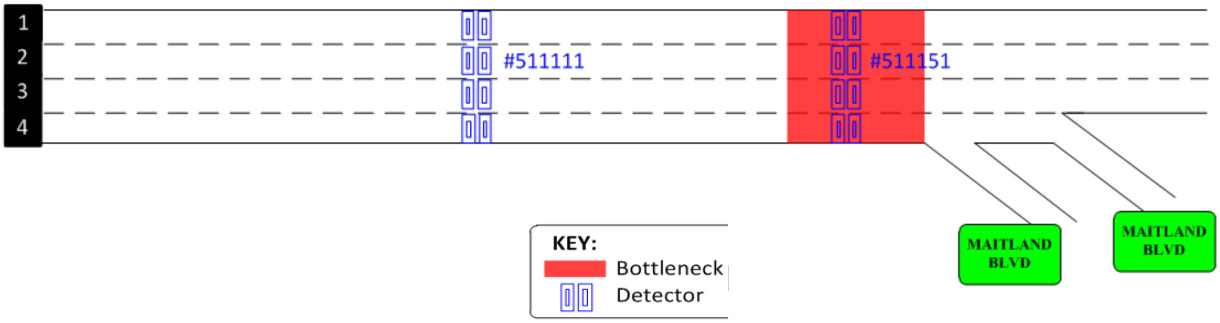

Figure 6.23 Location of downstream bottleneck

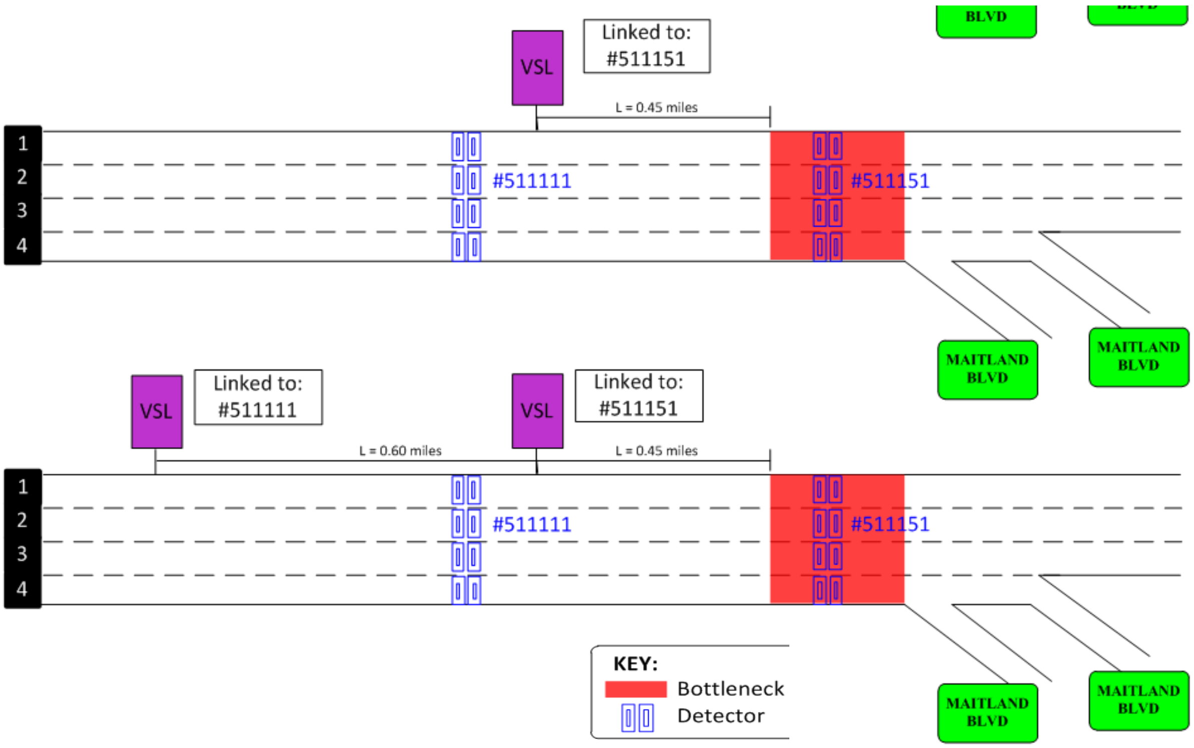

Figure 6.24 VSL sign placement scenarios a) 1 sign spaced one half mile from bottleneck; b) 2 signs spaced one half mile apart

Table 6.13 Simulation results using different sign locations at the downstream bottleneck

Scenario	**Total Travel Time (hours)**	**Average Speed (mph)**	**Total Travel Time (min)**	**Average Speed (mph)**
No Control	4332	46.81	31631	49.44
Existing Operations	4383	46.56	32882	48.87
Occupancy 1 Sign	4460	45.75	35357	47.15
Occupancy 2 Signs	4474	45.75	36101	46.23

The results again show no improvement over the existing operations in terms of average speed or travel time, and the no VSL scenario shows better operations compared to the four VSL scenarios. Also, the throughput displayed no noticeable improvement over the 12 time periods.

6.3.6 Alternate VSL Control Applied At the Main Bottleneck

Several additional different tactics were employed to attempt to alleviate the main bottleneck. Therefore, we tested two additional sets of threshold values for the occupancy algorithm, as shown in Tables 6.14 and 6.15.

Table 6.14 Occupancy thresholds for displayed speed limits (Alternate 1)

Traffic category	**Occupancy for decreasing speed limit (%)**	**Occupancy for increasing speed limit (%)**	**Speed limit (mph)**
Free flow	> 12	< 8	50
Light congestion	12- 20	8 - 15	40
Heavy congestion	> 20	< 15	30

Table 6.15 Occupancy thresholds for displayed speed limits (Alternate 2)

Traffic category	**Occupancy for decreasing speed limit (%)**	**Occupancy for increasing speed limit (%)**	**Speed limit (mph)**
Free flow	> 10	< 7	50
Light congestion	10 - 16	7 - 13	40
Heavy congestion	> 16	< 13	30

Also we tested two additional scenarios with full driver compliance: one using the occupancy-based algorithm and the second using the multiple parameter-based algorithm. Full driver compliance assumes that if the speed limit reduces by 10 mph, the drivers reduce their desired speed by 10 mph. These algorithms were tested using two signs spaced one half mile apart. The occupancy scenario used the existing thresholds (currently operating along I-4), and the multiple parameter used the thresholds shown in Figure 6.25.

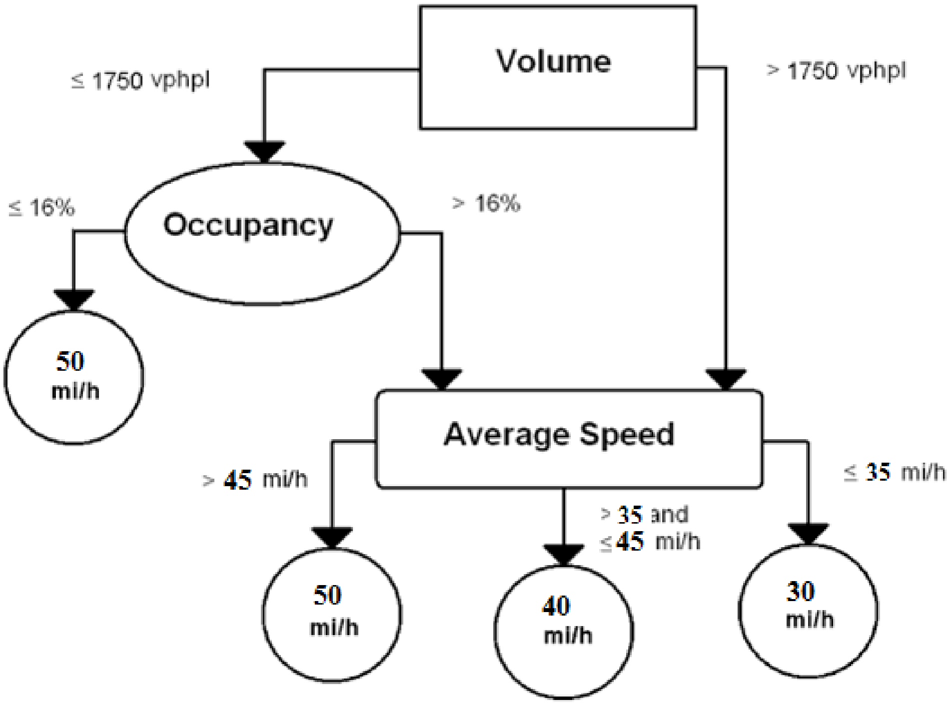

Figure 6.25 Decision tree logic for combined flow/occupancy/speed algorithm 100% compliance

The last scenario tested created a VSL zone upstream of the bottleneck. This VSL zone ends one half mile upstream of the bottleneck where a static speed sign is located. For this scenario the original occupancy-based algorithm was used, but linked to a detector at the bottleneck. The sign configuration and geometry are shown in Figure 6.26. The results of these alternative scenarios are shown in Table 6.16.

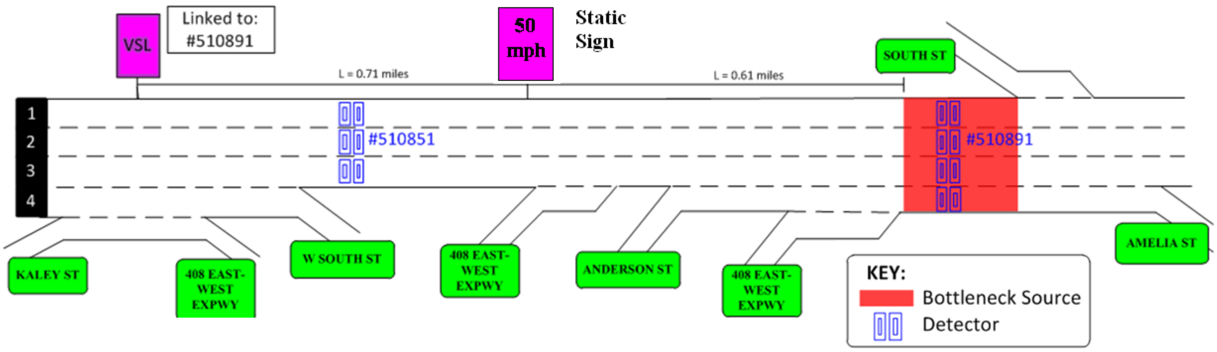

Figure 6.26 Sign configuration for upstream application of VSL signs

Table 6.16 Results of alternative mitigation for middle bottleneck

Scenario	**Total Travel Time (hours)**	**Average Speed (mph)**	**Local Total Travel Time (min)**	**Local Average Speed (mph)**
No VSL Control	4332	46.81	61649	39.47
Existing Operations	4383	46.56	63323	38.75
Occupancy 1 Sign Alternate 1	4361	46.82	61836	39.34
Occupancy 1 Sign Alternate 2	4415	46.30	60814	38.82
Multiple 2 Signs Full Compliance	4411	46.59	63545	40.27
Occupancy 2 Signs Full Compliance	4457	45.99	63493	40.33
Upstream VSL Zone	4344	46.76	62849	38.79

As shown, three of the scenarios showed some improvement of the local average speed over the existing operations as well as compared to the no-VSL scenario. The average speed over the entire corridor did not show much change, as the effects of the VSL were primarily concentrated around the bottleneck area.

6.4 Conclusions and Recommendations

This chapter reported on the findings of a series of simulation experiments to assess traffic operations along the I-4 VSL zone, with a variety of VSL algorithms and strategies. The scenarios evaluated considered three different VSL algorithms, various VSL sign location scenarios, different detector locations, and two levels of driver compliance. The I-4 VSL zone was first modeled in CORSIM and calibrated to replicate existing operations. VSL was tested along the entire corridor, as well as separately at three different bottlenecks identified along the I-4 VSL zone. A no-VSL scenario was also tested to compare operations with and without VSL. It was concluded that with the current VSL configuration of signs and detectors there was no observed operational improvement. The no-VSL scenario actually showed slightly higher speeds than any of the VSL scenarios. However, changing the detector configuration, and using the data from the worst performing detector, does have the potential to increase speeds and to improve operations for some VSL algorithms.

In testing each type of bottleneck separately we concluded that VSL can have a positive effect at a particular bottleneck. For two of the three bottlenecks we identified specific VSLs scenarios which would improve traffic operations relative to the existing VSL and also relative to the no-VSL case. In those cases, it is the local average speed that shows improvement. Examining the average network speed may not show much improvement, as the benefits are diluted (or even reversed) when averaging conditions along the entire freeway facility.

Overall, VSL may be able to provide some limited operational improvement at specific bottlenecks and/or along the entire network. However, there is no clear pattern regarding the type of algorithm that would be most beneficial at a particular bottleneck, nor any clear patterns regarding the VSL sign configuration. It seems however, that using the worst performing detector has the potential to improve the effectiveness of the VSL.

7 CONCLUSIONS

The overall objective of this project was to gain a better understanding of the drivers' perception of the I-4 VSL system, to evaluate operations along the VSL zone of the I-4, and to investigate VSL strategies that have the potential to improve operations along I-4. The major conclusions from each activity conducted throughout this project are provided below.

Focus Group Studies: On the basis of the responses obtained from the participants of the focus group studies, the following conclusions were drawn:

- The participants strongly recommended that the VSL system and its benefits should be promoted to the general public through the use of various media such as fliers, local news TV, internet, and radio.
- The participants indicated that they would typically not reduce their speeds unless the drivers/motorists in their surroundings reduce theirs.
- The participants suggested installing the VSL sign boards on both the sides of the roadway, and if possible, on the overhead sign boards at each lane.
- The participants were generally accepting of the use of automated law enforcement along I-4 if that would promote greater compliance with the reduced speed limits.

In-Vehicle Data Collection: On the basis of the data obtained from participants driving the instrumented vehicle, the following conclusions were drawn:

- Based on the driving experiment, it was determined that the displayed speed limit is often higher than the prevailing conditions, and at some points the speed limit displays reduced values when the freeway is at free-flow speed.
- A potential issue may be the accuracy of detector 510911 just before the exit to Amelia Street. It appeared that the occupancy values being relayed by this detector were too low for the prevailing speeds.
- Responses to the post-driving questionnaire were in agreement with the results from the focus group study. Drivers base their speed on the flow of traffic, and are minimally affected by the variable speed limit signs. The visibility of the signs may be an issue.

Larger more visible signs, or signs on either side of the road may help drivers recognize the displayed speed limit.

I-4 VSL Zone Assessment and Bottleneck Identification: From the results of the data analyses, the following conclusions were drawn:

- The on-ramp from SR-408 onto I-4 EB was found to be the major source of congestion along the eastbound direction during the AM and PM peak. During the PM peak, the on-ramps from Maitland Boulevard and Fairbanks Avenue were found to trigger congestion as well.
- The off-ramps to Amelia Street, SR-408 and Kaley Street from I-4 EB were often found to be congested during the day.
- The source of congestion along the I-4 WB direction was found to be outside the VSL zone, downstream of the on-ramps from Lake Mary Boulevard, SR-434 and Altamonte Springs.

Aerial Reconnaissance: On the basis of the aerial observations, the following conclusions were drawn:

- I-4 WB was not found to be congested during the morning hours on the section where the current VSL system exists. The westbound direction was found to be congested at the interchanges near Altamonte Springs, SR-434 and Lake Mary Boulevard.
- I-4 EB was found to be congested recurrently between 7:20 AM and 7:30 AM at the section where the on-ramp from SR-408 joins I-4 EB resulting in long queues up to Kaley Street.
- The off-ramps to SR-408 from both I-4 EB and WB merge with each other and results in formation of long queues in the respective EB and WB mainline corridor.
- The VSL system did not appear to ease the congestion along I-4 EB direction as queues were formed further downstream of the VSL sign location (for the VSL sign located at east of OBT and Fairbanks Avenue). However, few instances during the aerial sessions, it was felt that the VSL system helped in easing the congestion (for the VSL sign located at west of Ivanhoe Boulevard).

Development of Operational Improvements and Recommendations: From the network calibration and running alternate scenarios to improve the existing VSL system, the following conclusions were drawn:

- The current I-4 VSL algorithm was modeled in CORSIM and calibrated to replicate existing operations. Different scenarios were evaluated considering three different VSL algorithms, various VSL sign location scenarios, different detector locations, and two levels of driver compliance.
- With the current VSL configuration of signs and detectors there was no observed operational improvement, and when VSL control was removed speeds were slightly higher than the VSL scenarios. However, changing the detector configuration, and using the data from the worst performing detector, does have the potential to increase speeds and to improve operations for some of the VSL scenarios tested.
- VSL may be able to provide some limited operational improvement at specific bottlenecks and/or along the entire network. However, there is no clear pattern regarding the type of algorithm that would be most beneficial at a particular bottleneck, nor any clear patterns regarding the VSL sign configuration.

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APPENDIX A - Literature Review on Variable Speed Limits (VSL)

Static speed limits are designed to provide motorists with a safe speed at which to drive. While these safe speeds are effective during ideal conditions, they fail to provide recommended safe speeds during adverse weather or congested driving conditions (Sisiopiku, 2001). Thus, variable speed limits (VSLs) are implemented to commend safe driving speeds during less than ideal conditions. These systems can result in improved safety and possible performance improvements. This appendix summarizes first the literature review findings regarding implementation of VSLs, followed by research related to driver behavior around VSLs. The third part discusses evaluations of VSLs using simulation. The fourth part provides an overview of VSL algorithms, while the fifth part summarizes the types of VSL signs used.

Implementation of VSLs

The first part of this section provides an overview of VSL systems implemented in the US, while the second part summarizes the findings regarding implementations in Europe. Information regarding many of the evaluations was obtained from Robinson (2000). That report does not list the source documents of each evaluation, and thus it is difficult to obtain additional information regarding these evaluations.

Implementation of VSL in the USA

In the United States variable speed limits have been implemented in a number of locations. These systems typically set a safety speed limit according to the weather, traffic, or road conditions (CTC and Associates LLC, 2003; Abdel-Aty et al., 2006). Another use of variable speed limits are at school zones and at construction or work zone (Hines, 2002). The main objective of most freeway implementations in the US has been to improve safety, and very few have focused on congestion. Congestion-related benefits have been shown mostly using simulation. However, safety benefits have been documented for several of the systems.

The first variable speed limit system in the US was implemented along the M-10 (Lodge Freeway) in Detroit, Michigan, between the Edsel Ford Freeway (I-94) and the Davison Freeway in 1960. The system was designed to alert motorists to slow down when approaching congestion and accelerate when leaving a congested area. The system was 3.2 miles long and had 21 VSL sign locations. The speed limits were chosen by the operator based on CCTV and plots of freeway speed. The VSL signs were manually switched at the control center with an increment of 5 mph from 20 to 60 mph. The evaluation results showed that the VSL system did not significantly increase or decrease the vehicle speeds (Robinson, 2000). The system was disbanded sometime after 1967.

In New Jersey, a VSL system was implemented along the New Jersey Turnpike in the 1960s. This system was designed to reduce speed limits during congested conditions, and is currently part of a larger ITS system, that warns drivers of lane closures and crashes to improve safety and avoid large delays. The system is over 148 miles in length and utilizes approximately 120 signs. Since the implementation of the system there have been updates to controllers and detectors, but the system is still running without problems. The posted speed limits are based on average travel speeds and are displayed automatically. The posted speed limit can be reduced from the normal posted speed limit (65 mph, 55 mph, or 50 mph) in increments of 5 mph to a minimum speed of 30 mph under six conditions: vehicle collisions, traffic congestion, construction, icy road conditions, snowfall, and fog. No formal evaluation of the system has been performed, but the Turnpike Authority observes the system 24 hours a day and deemed its performance to be satisfactory. They did note that the system needed enforcement by State Police (CTC and Associates LLC, 2003; Steel et al., 2005).

In New Mexico, a VSL system was implemented along I-40 in Albuquerque in March of 1989. The system was set up as a test-bed for VSL equipment and was later disbanded in 1997 due to road widening. The six kilometer-long system used three roadside detector stations, and a variable message sign to vary the posted speed limit. The posted speed limit was generated using a look-up table based on the smoothed (90 percent old data plus 10 percent current data) average speed plus a constant based on the environmental conditions. The speed and environmental data such as light level and precipitation were collected by detectors. Evaluation results showed that there was a slight reduction in accidents after the system was implemented. It has been suggested that the implementation of the National Maximum Speed Limit (55 mph) hindered the effect of the system, as posted speeds were generated based on older data, and field conditions didn’t match the expected conditions. (Robinson, 2002; CTC and Associates LLC, 2003; Steel et al., 2005).

In Tennessee, a variable speed limit system was implemented along a 19-mile section of I-75 in 1993 to respond to the reduction in visibility causing crashes during adverse weather conditions (especially fog). The system has 10 VSL signs, 8 fog detectors, 44 radar speed detectors, highway advisory radio, and 6 swinging gates. The posted message and speed limit are determined by a central computer in the Highway Patrol office, based on the transmitted data collected using environmental sensor and vehicle detectors. The system has the capability to close down the entire stretch of roadway during severe fog conditions, and divert traffic onto US Highway 11. This requires coordination with highway patrol officers closing swinging gates. The effect of the VSL on actual travel speeds has not been formally evaluated, but the enforcement agency observed a slight (5 to 10 percent) reduction in speed, and there have been no crashes due to fog after the system was implemented (Robinson, 2002; Road Weather Management, 2003; Steel et al., 2005).

In Colorado, a variable speed limit system was implemented along the Eisenhower Tunnel on I-70 west of Denver in 1995. This system is designed to improve truck safety by displaying vehicle-specific safe operating speeds for long downgrades. The system consists of a weigh-in motion sensor, variable message sign, inductive loop detectors, and computer hardware and software. A safe speed is computed by an algorithm within the computer system based on the truck weight, speed, and axle configuration. The recommended safe speed is then displayed on a variable message sign. Moreover, each truck receives a vehicle-specific recommended safe speed message. The speed limit was advisory and evaluation results showed that truck-related accidents declined on the steep downhill grade sections after the implementation of the VSL system, even though the truck volume increased (Robinson, 2000).

The Washington Department of Transportation implemented a VSL system on I-90 across the Snoqualmie Pass in 1997. The system was implemented to improve safety and inform motorists of road conditions and weather information and is still active. Speed limits are recommended by the central computer based on information collected from a variety of sources, including wide aperture radar that tracks speeds, roadside cabinets that collect and control roadside data, and packetized data radio on three mountaintop relay sites that use microwaves to communicate to the control center. The computer automatically computes the speed from relayed data and recommends a VSL value, which an operator implements. It was found that VSLs may lose their effectiveness without enforcement by the State Patrol, and that they reduced the mean speed and increased the speed standard deviation (CTC and Associates LLC, 2003; TravelAid et al., 2001; Steel et al., 2005).

In 1998, Northern Arizona University and the Arizona Department of Transportation developed a VSL system based on a fuzzy control algorithm along the I-40 corridor in rural Arizona. This was an experimental system designed to display appropriate speeds for different weather conditions. It was unclear from the study whether the system was actually ever implemented, or just simulated. The system used a Road Weather Information System to gather atmospheric and road surface conditions. The system then displayed a corresponding speed limit according to the fuzzy control algorithm. Placer (2001) summarized upgrades made to this Road Weather Information System. No performance measures or quantitative impacts of the VSL system were given.

In 2000 a VSL system was implemented along I-80 in Nevada. The system was remotely controlled without human intervention. It consisted of four VSL signs (two eastbound and two westbound), visibility detectors, speed loops, RWIS weather stations, and “reduced speed ahead when flashing” signs upstream of the VSL signs. Speed limits were updated every 15 minutes and computed using a logic tree based on the 85th percentile speed, visibility, and pavement conditions. The results found that the sensors were unreliable and could not accurately relay visibility conditions (Robinson, 2000; Robinson, 2002). This limited the effectiveness of the VSL system. No information was found on the current operational status of the system.

In Florida, VMS were placed along a 9-mile portion of I-4 in Orlando. The system was installed from a period of September 2008 to January 2009. The system was designed to improve safety along I-4 through more steady flow during congested periods, and to provide advance warning of slowing traffic ahead. Detectors were used to measure speed, volume, and occupancy for each lane at 30-second intervals. The SunGuide software monitors the occupancy level and classified traffic conditions as either free-flow, light congestion, or heavy congestion. On the basis of these classifications, the software recommended speed limits of 30 mph for heavy congestion, 40 mph for light congestion, and the normal speed limit (i.e., 50 or 55 mph) for free flow. The software also ensured that the posted speed limit did not change by more than 10 mph between two adjacent sets of VSL signs (Haas et al., 2009). A study prepared for the FDOT evaluated the performance of the current VSL operation (PBS&J, 2009). The study concluded that the VSL system was not effective at reducing vehicle speeds because vehicles were not complying to the reduced speed limits. Since vehicles were not affected by the signs no traffic improvements or safety benefits were shown.

A study was conducted in southeast Wyoming (Young, 2010) to assess the effectiveness of VSL signs in a rural setting on a 100-mile stretch of I-80 through Elk Mountain. The system is designed to reduce speed limits during adverse weather conditions. When a reduced speed limit is in effect a yellow flashing light on top of the sign is activated and a reduced speed message is displayed. The study showed that vehicle speeds were reduced by 0.47 – 0.75 mph for every 1 mph reduction in posted speed (Young, 2010).

In Seattle, Washington variable speed limits have been installed recently on a stretch of I-5 from Boeing access road to I-90. The project began in 2009 with the installation of fifteen new overhead sign bridges. The system was activated in August 2010. The overhead signs feature individual displays for each lane and warn of approaching lane closures and traffic congestion. The project is designed to reduce the number of collisions and collision-related congestion. The displayed speed limit ranges from 40 mph to 60 mph, and is based on speed and volume data. The speed limit is enforced by the Washington State Patrol. There has yet to be a formal assessment of the effectiveness of the system (WSDOT, 2010).

Implementation of VSL in Europe

According to Hines (2002), numerous VSL systems have been implemented in European countries. Based on European case studies, he reported that VSLs can stabilize traffic flow in congestion and thus decrease the probability of crashes. A VSL system was implemented along an 18-km (11-mi) section of Autobahn 9 near Munich, Germany, in the 1970s. The system was originally implemented to improve safety, but the effects of the VSL system on other key parameters were also evaluated. The system displays speeds based on three control strategies: incident detection, harmonization, and weather conditions. Boice et al. (2006) investigated the effects of the system on key parameters around bottleneck formation, based on one-day data along the site. It was found that once a bottleneck had formed there was an 11% reduction in flow in the northbound direction and a 6% reduction in flow in the southbound direction. Capacity values were provided by lane and they were compared to the Highway Capacity Manual (TRB, 2000), and the German Handbuch für die Bemessung von Strassenverkehrsanlagen (FGSV, 2001). The capacity values for the median lane were consistent with both the HCM and the HBS values. The capacity value for the middle lane was consistent with the HBS but slightly lower than the HCM. The shoulder lane capacity was consistently lower than both manuals. It was concluded that there was no improvement in the capacity values over recognized standards.

In the Netherlands, a VSL system was installed along the A16 motorway near Breda in 1991. This system was designed to improve driving safety during fog conditions. The system has signs every 0.4-0.5 miles over 7.4 miles, 20 visibility sensors, and automatic incident detection. The speed limit was reduced to 80 km/h (50 mph) from 100 km/h (62 mph) if visibility dropped below 140 meters, and was reduced to 60 km/h (37 mph) from 100 km/h (62 mph) if visibility dropped below 70 meters. When an incident was detected, a speed limit of 50 km/h (31 mph) was posted on the first sign upstream and 70 km/h (43 mph) on the second sign upstream (Robinson, 2000). The results of an evaluation (Zarean et al, 1999) showed that drivers reduced their mean speeds by about 8-10 km/h (5-6 mph) during fog conditions. No information could be found on the current status of the system, but it was operational in 2000.

Another VSL system was installed in the Netherlands along a 20 km (12 mi) rural section of the A2 motorway between Amsterdam and Utrechtin in 1992 (Robinson, 2002).The system is designed to reduce the risk of shockwaves, crashes, and congestion. Variable message signs are spaced approximately every one kilometer and loop detectors spaced every half kilometer. The posted speed limits are determined by a system control algorithm based on 1-minute averages of speed and volume across all lanes. If an incident is detected, a speed of 50 km/h (31 mph) is displayed. The evaluation results showed that the severity of shockwaves and speed in all lanes were reduced (Van de Hoogen and Smulders, 1994). The vehicle speed and speed deviation decreased leading to fewer short headways as well as reduced severity of shockwaves. The study showed no positive effect on capacity or flow, but cited the safety benefits of traffic homogenization.

Speed limits were adjusted in England in response to the level of congestion on the M25 motorway in 1995. The objective of the system was to smooth traffic flow by reducing stop-start driving. The 22.6 km long system has VSL stations spaced at 1 km intervals, loop detectors at 500-meter intervals, and CCTV. Using loop detectors measuring traffic density and speed, speed limits are lowered in increments as congestion increases. The speed limits are lowered from 70 mph to 60 mph when volume exceeds 1,650 veh/h/ln, and lowered to 50 mph when volume exceeds 2,050 veh/h/ln. Results showed that traffic accidents decreased by 10-15% and there was a very high compliance with the VSL system (Robinson, 2000). The VSL system is still functioning today.

Rämä (1999) investigated the effects of weather-controlled speed limits and signs on driver behavior on the Finnish E18 site in Finland. The study looked at two scenarios compared to a control case: one in the summer where the maximum speed limit is 120 km/h (75 mph), and one in the winter where the maximum speed limit is 100 km/h (62mph). The control cases were the normal operating procedures in the summer and winter months. In the winter, during adverse road conditions the speed was lowered from 100 km/h (62 mph) to 80 km/h (50 mph). A 3.4 km/h (2.1 mph) decrease in speeds was observed. It was noted that during adverse conditions that are harder to observe by drivers (such as “black ice”), the VSL was very effective at reducing speeds compared to the control case. It was concluded that the system is very beneficial for improving safety when drivers have a difficult time perceiving adverse conditions. In the summer, results showed that the 85th percentile speed was decreased more than the mean speed, essentially reducing high end speeds. Both winter and summer scenarios showed that VSLs decreased the mean speed and standard deviation of speeds and demonstrated traffic homogenization. This was an experimental site and no information could be found as to the current status of the system.

Variable speed limits have been implemented in Sweden at 20 locations. Lind (2006) looked at the impacts of weather controlled VSLs on the E6 motorway in Halland, and the traffic controlled VSLs on the E6 in Mölndal, south of Gothenburg. The E6 in Mölndal is a low-speed urban motorway with normal speed limit of 70 km/h (43 mph). The VSLs in Mölndal were implemented as advisory speed limits in 2004 and changed to enforceable speed limits in 2006. This was part of a study to determine how VSLs were perceived by motorists in both enforceable and advisory conditions. The speed limit for free flow conditions was raised to 90 km/h (56 mph). In dense traffic the speed is reduced in a stepwise manner. At 950 veh/h/ln, the speed is reduced to 70 km/h (43 mph) and can be reduced to 50 or 30 km/h(31 and 17 mph) depending on the density. Two thirds of interviewed drivers indicated that they supported the VSL system and said that it made them more attentive as to changes in traffic conditions. The same proportion reported a less hectic driving scenario and reduction of queue lengths. When the advisory speed limit was displayed crashes were reduced by 20% and when the enforceable speed limit was displayed crashes were reduced by 40%. The results showed an increase in average speed for all driving conditions and as much as a 40 km/h (25 mph) increase in potential queue formation scenarios. The study concluded there was an improvement in driving behavior for congested conditions, and a homogenization of traffic.

Papageorgiou et al. (2008) studied the impact of VSLs on traffic flow behavior (flow-occupancy diagrams) through simulation of a motorway in Europe. The displayed speed was based on a threshold control algorithm, with possible speed limits of 60 mph, 50 mph, and 40 mph. The study showed that the 50 mph setting showed the most changes in traffic flow that could be used for improving traffic efficiency. The 40 mph setting was useful at high occupancies for displaying safe speeds, but not for improving traffic efficiency. The average occupancy was found to be higher when the VSL is implemented. The study concluded that the effect on capacity was not clear.

In summary, VSLs have been implemented in numerous areas throughout the United States, and are widespread throughout Europe. Table A.1 provides an overview of the VSL systems in the US, while Table A.2 provides an overview of these systems elsewhere. Most of the VSL systems in the US have been implemented to address adverse weather conditions. Several of the

European systems however have been implemented to smooth flow and reduce congestion-related crashes. Several studies showed that mean speeds will decrease when a VSL is implemented, indicating that the VSLs do affect the speed at which motorists drive. Several studies showed the speed standard deviation to decrease as well, and that decrease has been associated with safety benefits. There has been little evidence to suggest that implementing VSLs has the potential to increase capacity. The systems using weather and road conditions to display VSLs have been shown to reduce crashes and homogenize traffic conditions. It is important for VSL control algorithms to display a safe speed for drivers to travel, especially when dealing with adverse weather and road conditions.

Among active systems, the minimum speed limits provided in the US are typically between 40 mph and 50 mph, while those in Europe typically vary between 60 km/h (37 mph) and 80 km/h (50 mph). It is also common in European systems to display a speed of 50 km/h (31 mph) during a detected accident scenario.

Table A.1 Summary of VSL Systems in the US

Name	Location / Time	VSL Algorithm	Observed Impacts	Status/Goal of System
Michigan, USA	M-10 in Detroit /1960	Manually modified by operator based on CCTV and plots of freeway speed, from 20 to 60 mph	No significant effect on vehicle speeds	Inactive; improve safety by making drivers aware of downstream congestion
New Jersey, USA	New Jersey Turnpike / 1960s	Based on average travel speeds: normal speed to 48 km/h, 8 km/h increments	Authority concluded the signs are effective	Active;improve safety and reduce delays during congestion
New Mexico, USA	I-40 in Albuquerque/ 1989	Generated using a look-up table based on average speed plus a constant as a function of environmental conditions	A slight reduction in accidents, hindered by National Maximum Speed Limit (55 MPH)	Inactive;improve safety and smooth flow by displaying proper speeds
Tennessee, USA	19-mile section of I-75 / 1993	Determined by a central computer based on data collected using environmental sensors and vehicle detectors	5 to 10 percent reduction in speed, no crashes due to fog after implementation	Active;safety during adverse fog conditions
Colorado, USA	Eisenhower Tunnel on I-70 / 1995	Automatically computed based on the truck weight, speed, and axle configuration	Truck-related accidents declined on steep downhill sections	Active; improve truck safety on long downgrades
Washington, USA	I-90 across the Snoqualmie Pass / 1997	Automatically computed using speed, roadside data. Display confirmed by operator	Reduced the mean speed, increased the deviation	Active; improve safety by informing users of hazardous conditions
Arizona, USA	Rural section of I-40 in Flagstaff / 1998	Determined by a fuzzy logic controller based on atmospheric data and road surface conditions	Fuzzy logic worked well with the imprecision inherent in the input data	Inactive; improve safety during adverse weather conditions
Nevada, USA	I-80 / 2000	Using a logic tree, based on the 85th percentile speed, visibility, and pavement conditions, remotely controlled	Reliability of the visibility sensor limited the operation	Active; no specific consideration for congestion
Florida, USA	I-4 in Orlando / Sept/Oct 2008 and Jan 2009	Speed limits of 30 mph for heavy congestion, 40 mph for light congestion, normal limit for free flow	Analysis showed drivers were not complying with speed limits and system was ineffective	Active; improve safety and create a more steady flow
Wyoming, USA	Rural part of I-80 on Elk Mountain / 2010	Reduces speed during adverse weather	Speeds reduced by 0.47-0.75mph for every 1 mph reduction in VSL	Active; improve safety during adverse weather
Seattle, USA	I-5 from Boeing access road to I-90 / 2010	Algorithm unknown, bases changes on average speed and volume	No formal evaluation yet	Active; reduce accidents and congestion

Table A.2 Summary of VSL Systems Outside the US

Name	Location / Time	VSL Algorithm	Observed Impacts	Status/Reason for System
Germany	18-km section of Autobahn 9 near Munich / 1970s	Based on the fundamental relationships of speed, flow, and density between detector stations	Traffic during congested periods at speeds between 30 and 40 km/h	Active; stabilize traffic flow even under heavy flow conditions
Netherlands	A16 motorway near Breda /1991	Normal 100 km/h, reduced to 80 km/h if visibility < 140 m, reduced to 60 km/h if visibility < 70 m	Mean speeds reduced by about 8-10 km/h during fog conditions	Unknown; improve safety during fog
Netherlands	A2 between Amsterdam and Utrecht / 1992	Based on 1-minute averages of speed and volume across all lanes, 50 km/h if incident occurs	Severity of shockwaves and speed in all lanes were reduced	Active; reduce risk of shockwaves, crashes, congestion
England	M25 / 1995	Flow > 1650: 70 mph to 60 mph Flow > 2050:lowered to 50 mph (unit: veh/h/ln)	Accidents decreased by 10-15%, very high compliance	Active; smooth traffic flow, speed limits are enforced
Finland	E18 / 1998	Lowered from 100 to 80 km/h in winter, from 120 to 100 km/h in summer	Decreased both the mean speed and the standard deviation of speed	Active; influence driver behavior and improve safety; speed limits are mandatory
Sweden	E6 motorway in Mölndal / 2006	Based on density: Free flow = 90 km/h 950 veh/h/ln= 70 km/h Can be reduced as low as 50 to 30 km/h	Advisory = 20% crash reduction Enforceable = 40% crash reduction Average speed increase Homogenization of traffic Reduction in queue length	Active; improve safety during adverse weather conditions
Europe	Motorway in Europe (2008)	Based on a threshold control algorithm	Efficiency optimized at 50 mph. Capacity effects not clear.	Specific location not provided; improve traffic flow efficiency

Driver Behavior Around VSLs

One of the important issues in implementing VSLs which is crucial to their success is whether drivers will obey the speed limit signs. This section summarizes the literature regarding driver behavior around VSLs and driver acceptance of such systems.

In the Netherlands Van den Hoogen and Smulders (1994) studied the VSL system on sections of the A2 motorway between Amsterdam and Utrecht (this is the same section as discussed earlier in the literature review). A user survey showed driver acceptance of the system was good, and the consensus from drivers was that it resulted in less stressful driving.

Tignor et al. (1999) suggest that the key to gaining compliance of variable speed limits is automated enforcement. Automated speed limit enforcement is not common in the United States, but has shown great benefits in Europe. The study by Tignor et al. (1999) in England showed improvements of compliance to VSLs due to automated enforcement. These improvements to compliance also improved facility performance measures with a 5-10% increase in the roadway capacity, and a 25-30% decrease in the number of rear-end collisions. After the initial installation of auto-enforcement cameras, they discovered that they did not have to keep cameras in every enforcement station. The flash produced by the cameras was enough to deter users from exceeding the speed limit as long as there were active cameras at a few locations. They could rotate the locations of actual cameras so drivers would never know which cameras were actually taking pictures.

Rämä (2001) studied the effect of weather controlled speed limits on driver behavior in Finland. The study took place in two scenarios; one in the winter and one in the summer. During the winter the study experimented with increasing the speed limit from 80 km/h to 100 km/h during good road conditions, and displaying a slippery road message during adverse road conditions at the normal speed limit (80 km/h). It was shown that during poor weather conditions in the winter, providing a warning message as well as the normal speed limit (80 km/h) reduced mean speed by 2.5 km/h. If the normal speed limit was displayed during poor conditions without a warning message, the mean speed was higher. During good road conditions and operating at the normal speed limit, the average speed was lower when compared to that measured when a static speed sign was present. When during good road conditions the speed limit was increased to 100 km/h, the average speed increased by 3.9 km/h. This shows that drivers recognize the displayed speed as the maximum they should travel, and also as the safest recommended speed. In the summer the normal speed limit is 100 km/h and the speed could be reduced to 80 km/h during adverse road conditions. During the summer, when the speed limit was reduced to 80 km/h the average travel speed decreased by 3 km/h. When the normal speed was displayed during good road conditions the average travel speed increased by approximately 1 km/h. In both summer and winter scenarios if the 100 km/h speed limit was shown during poor conditions the average speed increased and the headways decreased causing short headways and unsafe conditions. The percentage of drivers recalling the displayed VSL speed in both scenarios was good compared to fixed signs, and there was an overall positive response to the system. The author suggested that there would be more of an acceptance of VSLs if the driver was aware of why the speed limits were being reduced. He surmised that if the driver knew the theory behind the VSL system they might be more accepting of it.

Ulfarsson et al. (2005) looked at the effect of variable speed limit signs on mean speeds and speed deviations. They concluded that VSLs significantly reduce mean speed and that speed deviation was decreased for the uphill direction, but increased for the downhill direction. They recommended that VSLs should only be used under adverse weather or traffic conditions. They show that during favorable conditions VSL signs increased the average speed and speed deviation, leading to unsafe conditions. The study also analyzed an area downstream of the VSL section and suggested that while reducing speeds is effective within the variable speed limit zone, drivers may compensate by driving faster once out of a reduced zone which can lead to short headways and dangerous conditions downstream.

Brewer et al. (2006) investigated the effectiveness of several speed control devices on compliance of speed control in work zones. The study investigated the effectiveness of three separate devices: a speed display trailer, changeable message sign with radar, and orange border speed limit signs. The results showed that drivers will reduce their travel speed when their actual speed is displayed by radar detection signs. Radar devices show great potential for increasing speed compliance. Adding an orange border to a speed sign increases the visibility of the sign but does not greatly increase the compliance. Based on data from the study, the authors concluded that drivers will travel at the speed at which they feel the most comfortable, unless they are aware of potential enforcement.

Lee and Abdel-Aty (2008) investigated the effects of warning messages and variable speed limits on driver behavior using a driving simulator. He found that under congested conditions and during gradual transitions of speed limits drivers followed speed limits well. If the speed was reduced abruptly there was greater speed variation and shorter headways. The use of a gradual reduction of speed limits reduced the variation in speeds and resulted in safer conditions. The author recommended placing VSLs upstream of the congestion and to gradually reduce the speed limit for a smooth transition. He concluded that VSLs are effective at reducing mean speeds and variation of speeds in congested areas. He also noted that the use of a simulator may not depict real world driving situations as the driver is aware that someone is monitoring their speed.

A study by PBS&J (2009) assessed the effectiveness of the current VSL system implemented on a 9-mile stretch of I-4 in Orlando, FL. The study analyzed driver speed through correlation testing. It was determined that driver's speeds were reduced by the VSL signs but that occupancy had increased as well. It was also shown that most of the traffic exceeded the speed limit by more when the VSL was reduced compared to the baseline speed limit. Through hypothesis testing it was also shown that flashing beacons had no significant effect on speed compliance rates, meaning they were ineffective at increasing compliance rates. Overall the study concluded that a true assessment of the system is not possible because the drivers were not traveling at speeds displayed by the signs. The speeds were correlated to the occupancy values; however the average speeds and occupancies were not correlated to the posted VSL speed.

Trout et al. (2010) studied the effectiveness of different work zone speed limit displays on driver behavior through use of a laboratory survey. The study compared four types of signs: static work zone, electronic speed limit, portable changeable message signs, and “Your Speed” signs. The study recommended the use of electronic speed limit signs using white LEDs in order for the sign to be perceived as enforceable. However, 97% of people found both the white and orange LED signs to be enforceable.

In summary, research has shown that drivers tend to travel at their desired speed whenever there is no enforcement. Automated enforcement, highway patrol enforcement, and signs that display drivers' speeds have all shown to be effective enforcement strategies. In Europe most systems have had a positive response from drivers, and previous studies have concluded that drivers are more accepting of these systems if they know why they are implemented. The effectiveness of a VSL system is dependent on the driver's acceptance of the system. Gaining increased compliance of variable speed limits can be accomplished through some method of enforcement, or by making drivers aware to the specific strategies of VSL implementation. Research also suggests that gradual speed limit reduction is more effective than sudden speed reduction.

Evaluation of VSLs Using Simulation

Simulation is a very valuable tool for assessing the impact of changes in the transportation system and selecting optimal alternatives without actually implementing and testing them in the field. Several studies have been conducted to evaluate various VSL algorithms prior to their implementation. This section provides an overview of such studies and summarizes their findings.

Hegyi et al. (2003) present a predictive model for coordination of variable speed limits to suppress shockwaves at highway bottlenecks. The objective of this control mechanism is to minimize the time a vehicle spends in the given network. The METANET model is used to simulate the network, but was modified to incorporate the effect of speed limits into the calculation logic. METANET is a second order macroscopic traffic flow model. The controller predicts the evolution of the network based on the current state of the network and a control input. The algorithm bases speed increments through real time calculations of traffic flow, density, and mean speed. Safety constraints are implemented into the model to prevent large speed limit fluctuations (e.g., 10 km/h). The model was applied to a benchmark freeway segment consisting of two nodes connecting one link. The study compared the use of continuous-valued speed limits and discrete valued speed limits to a base scenario with no control. The results showed that in all control cases the coordination of speed limits eliminated the shockwave, and restored the volume exiting the section to capacity sooner.

Hegyi et al. (2005) continued work on model predictive control through coordination of VSLs and ramp metering. The study compared the results of simulated ramp metering, and ramp metering with variable speed limits on a simple network. The results showed that when used in conjunction the total time spent in the system was lower and resulted in higher outflow. The decision of which method to use depends on the demand of the on-ramp and the freeway. It is suggested that VSLs should be used if speed limits can limit the flow sufficiently, however if the flow becomes too large, ramp metering should be implemented. The authors suggest that integrated use of both technologies will produce more favorable results than the use of each technology by itself.

Lin et al. (2004) presented two online algorithms for VSL controls at highway work zones. The first VSL algorithm was aimed to reduce approaching traffic speed so as to increase the average headway for vehicles to merge onto adjacent lanes. It consisted of two modules: one to compute the initial speed of each VSL sign, and the second responsible for updating the displayed speed on each VSL sign. The algorithm computes the appropriate speeds starting on the link directly upstream of the work-zone. The algorithm computes the target density and appropriate speed for that segment and works upstream to calculate appropriate speed limits. The second VSL algorithm was aimed to maximize the total throughput from the work zone under some pre-defined safety constraints. The model looks at projected queue lengths and changes the upstream speed control signs based on the optimization of a throughput function. The simulation results by CORSIM indicated that VSL algorithms can increase work-zone throughputs and reduce total vehicle delays. Moreover, when VSL was implemented, speed variances were lower than other non-controlled scenarios, although the average speed didn’t change significantly.

Lee et al. (2004) used a real-time crash prediction model integrated with the microscopic simulator PARAMICS to assess the safety effects of variable speed limits on a 2.5 km stretch of a sample freeway segment. The algorithm for changing speeds was relatively simple. Three detector locations relay information to the controller which averages their values into one crash potential value. A crash threshold is predefined, and when the crash potential exceeds this threshold the speed limit for all three detector locations was set based on a set of criteria. When crash potential exceeded the threshold, the speed limits were reduced from the design speed limit

(90 km/h) based on the average speeds: reduced to 50 km/h if average speed ≤ 60 km/h, reduced to 60 km/h if average speed > 60 and ≤ 70 km/h, reduced to 70 km/h if average speed >70 and ≤ 80 km/h, and reduced to 80 km/h if average speed > 80 km/h. The results found that reduction in speed limits can reduce average total crash potential, and the greatest reduction in crash potential occurred at the location of high traffic turbulence such as a bottleneck. However, the reduction in speed limit also increased the travel time. Thus, there was a trade-off between safety benefits and system travel time increase. The results were not based on real traffic data and many assumptions in the simulation were not calibrated to field conditions. The authors speculated that this may account for the increase in travel time.

Lee et al. (2006) continued work using the simulator PARAMICS in combination with the real-time crash prediction model described earlier, to analyze the effect of variable speed limits on safety. Simulation results showed that the system obtained the greatest safety benefit when speed changes were gradually introduced (5 mph every 10 minutes). It was also found that it is best to base the displayed speed on the average speed of detectors immediately upstream and immediately downstream of the VSL location. However, the study has several limitations. First, it assumed that drivers would comply with the speed limit. Second, it ignored the potential of driver compensation (driving faster downstream after reducing speed).

Mitra and Pant (2005) evaluated the impact of a VSL system on a freeway work zone using the model VISSIM. The authors considered three scenarios: base scenario (no work zone), reduced speed on the work zone link, and reduced speed with reduced lane width. The displayed speed was only changed through the work-zone and only one value indicating lowered speed was displayed. Through analysis of the data, a process was carried out for developing an equation to calculate expected delays for a reduced speed through a work zone. The authors concluded that this equation could help determine the proper speed through a work-zone without the use of repeated simulation.

Abdel-Aty et al. (2006a) evaluated the safety effects of variable speed limits on I-4 in Orlando, Florida using PAPAMICS. This was part of a series of papers which reported research related to the I-4 system. The algorithm not only investigated lowering speeds upstream of congestion, but also raising speeds limits after a congested area. The VSL signs were changed based on data from a detector directly associated with the sign. The study evaluated two speed regimes: low speed, and medium to high speed. The results found that there was a safety benefit in medium-to-high-speed regions but not in low-speed situations (congested situations). It was also shown that the greatest improvement in safety was achieved by abruptly changing speeds (15 mph) rather than gradually changing them. A travel time study was also conducted and showed a significant reduction in travel time through the segment. It was further recommended that decreasing speed limits before congestion and increasing them after congestion has positive impacts on safety and travel time.

In a subsequent study, Abdel-Aty et al. (2008) studied the effects of VSL on reducing crash risk on I-4 at different volume loading scenarios using PARAMICS. There were a total of 24 treatments in the experiment based on the extent of speed change, speed change distance, and speed change duration (5 to 10 minutes). The study investigated the benefits of reducing the speed (5 -10 mph) entering a congested area and increasing the speed (5 mph) past the congested area. Crash risks were computed from a crash prediction model that was based on traffic parameters. The study found that VSLs could reduce the rear-end and lane-change crash risk at low volume conditions, especially when lowering the upstream speed limit by 5 mph and raising the downstream speed limit by 5 mph. Again, VSLs were not found to be effective in reducing crash risk during congested conditions.

Abdel-Aty and Dhindsa (2007) also conducted a micro-simulation study using PARAMICS in order to determine the impact that VSLs and ramp metering would have on the safety of a 9-mile stretch of I-4 in Orlando. The study also investigated the impact of VSLs and ramp metering on operational parameters like speed and travel time. The speed limits were changed based on thresholds of 5 minute averages of travel speed, and the ALINEA feed-back algorithm was used for the ramp metering. It was concluded that implementation of VSL can increase average speeds and decrease speed variation in the network as well as improve the risk index. It was also shown that the best implementation strategy is one where the speeds are incremented by 5 mph over a half mile. It was also shown that for safety improvements, a scenario where only downstream speeds are increased, outperformed a scenario where upstream speeds are decreased and downstream speeds increased. A third conclusion drawn by the authors was that VSL and ramp metering are more effective when integrated together. When used in conjunction they showed shorter travel times and higher speeds than ramp metering or VSL alone.

Jiang and Wu (2006) used a cellular automaton model and showed that using multiple speed limits (where the speed limits decrease gradually from upstream to downstream) can help remove traffic jams. For a single small jam the concept is that by altering the speeds appropriately one can decrease the inflow toward a jammed area and increase the outflow. This will eventually result in the jam being dissipated. Their model was not based on field data.

Allaby et al. (2007) evaluated the impact of a candidate VSL system on an 8-km section of the eastbound Queen Elizabeth Way, an urban freeway in Toronto, Canada. The study was conducted using the microscopic simulator PARAMICS combined with a categorical crash model developed by Lee (2004). The VSL algorithm used was based on a logic tree that uses threshold values for flow, occupancy, and average travel speed. The base speed used was 100 km/h (62 mph) and it could be reduced to 80 km/h (50 mph) and 60 km/h (37 mph). The signs were arranged so there was never an abrupt change of speed limits (10 km/h difference) between signs. Each VSL sign was linked to an adjacent loop detector, and each sign operates individually. The results of the simulation showed that implementation of VSL signs could significantly improve safety, however the authors concluded that the use of VSL signs increased the travel time for all traffic scenarios considered.

Piao and McDonald (2008) assessed the safety benefits of in-vehicle variable speed limits on motorways using the microscopic simulation model AIMSUN. Traffic on UK motorway M6 with speed limit of 70 mph was simulated under different scenarios. Variable speed limits were applied when the speed difference between a queuing section and the upstream section was larger than 20 km/h (12.4 mph), and were provided to drivers through in-vehicle information. The simulation assumed that all vehicles were equipped with the in-vehicle devices. The adjusted speed limits could be 60km/h (37 mph), 70 km/h (43 mph), 80 km/h (50 mph), 90 km/h (56 mph), or 100 km/h (62 mph). The simulation results showed that VSL reduced speed differences creating homogenization, reduced very small time headways, small time-to-collision (TTC) events, and lane change frequency. This in effect reduced crash potential. The authors also indicated that there were potential safety risks in using the in-vehicle VSL compared with roadside VSL: large speed variations in speed could occur because some vehicles didn’t have the in-vehicle device.

Papageorgiou et al. (2008) used a quantitative model to investigate the impact of VSL implementation on traffic flow. VSLs were incorporated into the general second-order traffic flow model METANET as a control component. The study evaluated the system based on a no-control case, coordinated ramp metering, VSL, and integrated scenario. The freeway was set up as a constrained discrete-time optimal control problem and solved using a feasible direction algorithm. It was shown that VSLs can substantially improve the traffic flow efficiency of a stretch of roadway especially when combined with coordinated ramp metering. The study concluded that when the optimal solution is applied to real motorway traffic, the solution will inevitably become non-optimum due to uncertainties in the real traffic stream. It is suggested that future research address using the optimal solution to develop a suitable feedback control strategy and update the solution in real time.

Carlson et al. (2010) expanded on the work of Papageorgiou (2008) by using a similar method, to explore the parallels between ramp metering and applying VSL upstream of a potential bottleneck or high volume merging situation. The METANET second order macroscopic model was altered to allow the VSLs to be incorporated. The study showed that when applied upstream, the VSL can act similarly to ramp metering where the flow is held back on the mainstream rather than on the ramp. The traffic arriving at the bottleneck is temporarily reduced and the system delays propagation of the congestion. Four scenarios were evaluated: no-control, VSL control, ramp metering, and integrated control. The VSL case decreased total time spent in the system (TTS) by 15.3%, and when VSLs and ramp metering are used in conjunction the TTS was reduced by as much as 19.5%. The study concluded that traffic flow and capacity can be improved through VSL use by reducing the capacity drop at bottlenecks. However, if the VSL is applied at under-critical conditions without the potential for bottleneck mitigation, mean speed is lowered and flow efficiency is decreased.

Popov et al. (2008) proposed a speed limit control approach to eliminate shockwaves based on a distributed controller design. The METANET environment was used for the simulation. In this design, each variable speed limit sign has its own controller, but they all use the same structure and parameters. The proposed method requires using the appropriate amount of upstream and downstream data. Different scenarios were presented where each controller uses data from as many as 5 downstream controllers and one upstream controller. The maximum speed limit was 120 km/h (75 mph), and could be lowered in increments of 10 km/h to a minimum of 50 km/h (31 mph). The authors showed that a simple, linear, static controller using immediate neighbor information successfully resolves a shockwave. The control scenario when compared to a scenario without controllers reduced total time spent in the network by 20%.

Ghods et al. (2009) used METANET to investigate the use of ramp metering and VSL in order to reduce peak hour congestion. An adaptive genetic fuzzy control was used and was compared to the traditional ALINEA controller. Local density, local speeds, and queue length of the on-ramp were used as input data to develop the fuzzy controller. The fuzzy controller processes this input data and provides a corresponding metering rate and two variable speed limits. The idea behind fuzzy logic is to have a controller that resembles human decision making. It can process imprecise input data to arrive at a definitive conclusion. Rather than having precise threshold values that determine the output values of the controller, approximate multi-valued boundaries are used. This allows for input data to have partial membership to a category as opposed to the traditional "crisp" membership or non-membership options only. The study showed that the genetic fuzzy ramp metering and VSL control improved TTS by 15.3%.

In summary, much research has been conducted on the potential benefits of VSLs through the use of simulation. Table A.3 provides an overview of the studies discussed. One set of studies has used VSLs as a control mechanism similar to that employed in ramp metering. These studies concluded that VSLs can be used to suppress shockwaves at bottlenecks by implementing the VSL upstream of a bottleneck. Those studies reported that VSLs were effective in reducing TTS in the network, and their effect was more beneficial when combined with ramp metering. Another set of studies investigated the use of VSLs in microsimulators (VISSIM, PARAMICS, AIMSUN) and evaluated the safety benefits of such systems. These studies generally conclude that VSLs can improve safety, as they tend to reduce speed variability.

Table A.3 Summary of VSL Evaluations Using Simulation

Author	Software	VSL Algorithm	Impacts	Other Comments
Hegyi et al. (2003)	METANET	Modified the METANET model to incorporate variable speed limits using continuous-valued speed limits based on the fundamental diagram.	Damped shockwaves and decreased the total travel time	Used a safety constraint to prevent large speed limit drops (e.g., 10 km/h)
Lin et al. (2004)	CORSIM	Two online algorithms: 1. minimize the queue in advance of the work zone by dynamically reducing the speed limit. 2.maximize the throughput over the entire work-zone area	Increased work-zone throughputs and reduced total vehicle delays, lowered speed variance	Evaluated the algorithms on three types of work zones. Used speed variances as safety indicator
Lee et al. (2004)	PARAMICS	50 km/h if ave.speed ≤ 60 km/h, 60 km/h if 60 <ave.speed ≤ 70 km/h, 70 km/h if 70 <ave.speed ≤ 80 km/h, 80 km/h if ave. speed > 80 km/h	Reduced average total crash potential, especially at the bottleneck. Increased the travel time	Results were not based on real traffic data, many assumptions not calibrated
Mitra and Pant (2005)	VISSIM	Three scenarios: base, reduce speed on one link, reduce speed with lane width variation on link	Significant changes in speed, density, and lost time when reduced speed is implemented with lane width variation	Limited to a static network modeling due to scope and data
Hegyi et al. (2005)	METANET	Use of ramp metering with variable speed limits to provide optimum control.	TTS was lower and a higher outflow was achieved.	Did not perfect method for switching from ramp metering to VSL but gave general guidelines
Abdel-Aty et al. (2006a)	PARAMICS	Lower speed limits upstream and higher speed limits downstream of a hazard location	Safety benefit in medium-to-high-speed regions, travel time reduced, no benefit in congested situations	
Lee et al. (2006)	PARAMICS	Speed limit change for a pre-specified duration if the estimated crash potential (predicted from loop detector data) exceeded a specific threshold	Most safe when speed limit equal to the average speeds at the upstream and downstream detectors	Assumed that drivers would comply with the speed limit. Ignored the potential of driver compensation
Jiang and Wu. (2006)	Cellular Automation Model	Used multiple speed limits at a traffic jam: Used decreased speed limits at the jam and increased the speed limit gradually upstream.	Traffic jams were shown to dissipate faster than the control case when the new varied speed limits were in place.	The speed limit reduction resulted in lower flow into the jammed area

Table A.3 Summary of VSL Evaluations Using Simulation (continued)

Author	Software	VSL Algorithm	Impacts	Other Comments
Allaby et al. (2007)	PARAMICS	Uses a logic tree based on flow, occupancy, and average travel speeds.	Improved safety but increased travel time for all traffic scenarios	Used several different combinations of threshold values to get optimum solution
Abdel-Aty and Dhindsa (2007)	PARAMICS	Used 5 minute averages of speed to determine switching. Used 5 mph and 10 mph increments.	Improved speeds and decreased speed variation. Improved the risk index.	Used 24 scenarios to identify best implementation of upstream and downstream increments
Piao and McDonald (2008)	AIMSUN	In-vehicle system, could be 60km/h, 70 km/h, 80 km/h, 90 km/, and 100 km/h	Reduced speed differences, small time headways, small time-to-collision (TTC) events	Needed in-vehicle device. Need to study how to achieve balance of safety and efficiency
Abdel-Aty et al. (2008)	PARAMICS	24 treatments based on the speed change extent (-10 to 5 mph), speed change distance, speed change duration (5 to 10 minutes) et al.	Reduced rear-end and lane-change crash risk at low volume conditions. No safety benefit in congested situations	crash risk were computed from crash prediction model that based on traffic parameters
Papageorgiou et al. (2008)	METANET	Modified METANET environment to incorporate variable speed limits and ramp metering.	VSL improved traffic flow efficiency, especially when used in conjunction with ramp metering	Considered no-control, VSL, ramp metering, and integrated cases.
Popov et al. (2008)	METANET	Used upstream and downstream data, and based threshold values on the fundamental diagram of flow and density.	Shockwave was resolved and total time spent was reduced by 20% when compared to the no control scenario.	
Ghods et al. (2009)	METANET	Used local density, local speeds, and queue length of the on-ramp to develop the fuzzy controller	ALINEA ramp metering controller: 4.8% Genetic fuzzy ramp metering controller: 5.0% Genetic fuzzy ramp metering and VSL: 15.3% (percentages signify improvements in TTS)	The genetic fuzzy control proved to be superior to the ALINEA control.
Carlson et al. (2010)	METANET	Modified METANET to incorporate VSL data through use of a b-value	Reduced TTS by 15.3% in VSL case and 19.5% in integrated case	Four scenarios: no-control, VSL, ramp metering, and integrated

VSL Algorithms

This section provides more detailed information regarding the various VSL algorithms that have been developed. Different algorithms have been developed based on the purpose of the VSL. The first part of this section discusses VSL algorithms developed to mitigate congestion and improve safety, while the second part focuses on algorithms developed to address weather and other issues.

Congestion and Safety-Related Algorithms

The following three algorithms aim to mitigate shockwaves and are based on a combination of parameters:

- **Along A2 between Amsterdam and Utrechtin / 1992 Netherlands (implemented)**
    - Based on 1-minute averages of speed and volume across all lanes
    - 50 km/h if incident occurs
    - Severity of shockwaves and speed in all lanes were reduced
    - Detailed information regarding location of signs and detectors was not provided
- **Hegyi 2003 (METANET simulation, not implemented)**
    - Base speed increments through real time calculations of traffic flow, density, and mean speed
    - Uses rolling horizon values to continuously update the optimal solution
    - Showed that during a developing shockwave the model predictive control created a scenario with less congestion and higher outflow
- **Popov et al. 2008 (METANET simulation, not implemented)**
    - Used individual controller for each VSL sign using data from as many as 5 downstream controllers and one upstream controller
    - Reduced speeds in 10 km/h increments from 120 km/h to as low as 50 km/h

  - Showed that a simple, linear, static controller using immediate neighbor information successfully eliminates a shockwave

The following two algorithms are based on flow:

- **M25 / 1995 England (implemented)**
  - When flow > 1650 veh/h/ln: 70 mph to 60 mph.
  - When flow > 2050 veh/h/ln: lowered to 50 mph
  - Accidents decreased by 10-15%, very high compliance
  - Detailed information on location of signs and detectors not provided
- **On the E6 motorway in Mölndal / 2006 Sweden (implemented)**
  - Free flow = 90km/h
  - 950veh/h/ln = 70 km/h
  - Speed can be reduced as low as 50 to 30 km/h
  - When speeds were advisory there was a 20% crash reduction observed. For enforceable speed limits the crash reduction improved to 40%. Other impacts included average speed increase, homogenization of traffic, and reduction in queue length.

The following algorithm is based on occupancy:

- **I-4 Orlando, Florida (implemented)**

The software, SunGuide, uses in-ground inductive loops to measure traffic speed, volume, and occupancy for each lane in both directions of I-4. The speed displayed on the VSL sign depends upon the traffic occupancy level observed by these inductive loops. Each sign is linked to two or three downstream detectors and the occupancy value is averaged between them. There are three categories of traffic for this system: free, light, and heavy. The SunGuide software recommends an increase or decrease in speed based on the current occupancy level. An operator at the District 5 Regional Traffic Management Center either accepts or declines the recommendation. Table A.4 provides the thresholds used by the I-4 system to set variable speed limits.

Table A.4 Orlando I-4 Control Thresholds

	Occupancy for Decreasing Speed Limit	Occupancy for Increasing Speed Limit	Speed Limit
Free Flow	< 16%	< 12%	50 mph
Light Congestion	16 - 28%	12 - 25%	40 mph
Heavy Congestion	> 28%	>25%	30 mph

For the software to recommend a change between categories, the occupancy level must be sustained and observed for at least 120 consecutive seconds.

The following algorithm is based on average travel speeds:

- **Lee et al. 2004 (PARAMICS simulation, not implemented)**
    - Each VSL has an associated loop detector located adjacent to it
    - Three signs are grouped together and data for these signs was averaged into one value
    - If a crash potential threshold is reached the displayed speed is dropped at all signs using a set of criteria (all signs display the same speed)
    - 50 km/h if ave.speed ≤ 60 km/h,
    - 60 km/h if 60 <ave.speed ≤ 70 km/h,
    - 70 km/h if 70 <ave.speed ≤ 80 km/h,
    - 80 km/h if ave. speed > 80 km/h
    - Reduced average total crash potential, especially at the bottleneck, but increased the overall travel time

This algorithm is based on a combination of flow, occupancy, and average speed, using a logic tree.

- **Allaby et al. 2007 (PARAMICS simulation, not implemented)**
  - Figure A.1 summarizes the logic used in this algorithm.
  - Each VSL sign is linked to an adjacent detector that operates individually
  - For low volumes (less than 1,600 vphpl) occupancy is used as part of the criteria for reducing speeds. For higher volumes (more than 1,600 vphpl) occupancy is not considered.
  - Ultimately average speed determines the displayed speed. This algorithm does not address gradual speed limit reduction as drivers are approaching the bottleneck.
  - The simulation results showed that VSL signs could improve safety but that the travel time for all traffic scenarios considered were increased.

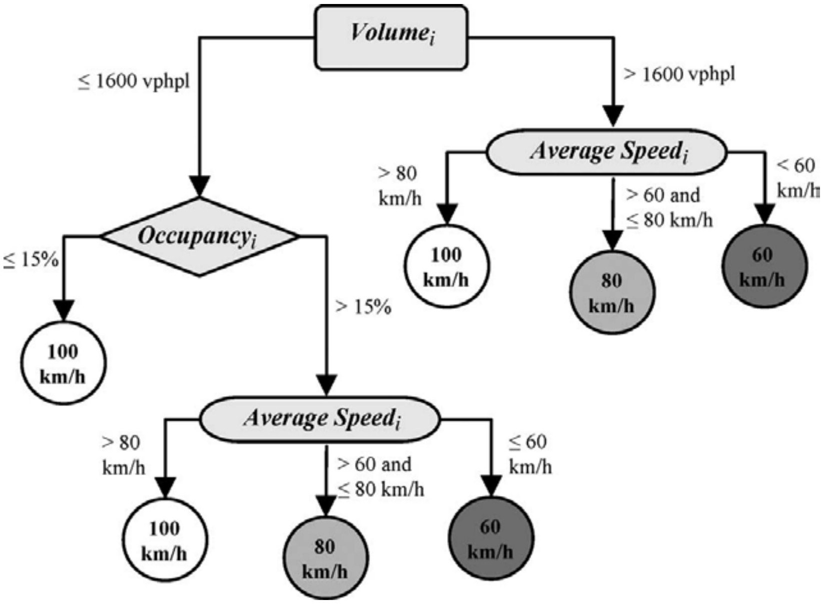


Figure A.1 Decision path for determining the new posted speed of the trigger VSLs. (Source: Allaby P., Hellinga B., and Bullock M. Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications. IEEE Transactions on Intelligent Transportation System, 2007. Vol.8, No.4, pp.671-680)

Weather-Related and Other Algorithms

The following four algorithms were developed to address weather-related issues (visibility, wind speed, precipitation severity, etc.):

- **Along A16 motorway near Breda /1991 Netherland (implemented)**
    - 100 km/h (normal)
    - 80 km/h if visibility < 140 meters
    - 60 km/h if visibility < 70 meters
    - Mean speeds reduced by about 8-10 km/h during fog conditions
- **25 km, between Hammina and Kotka / 1997 Finland (implemented)**
    - 120 km/h for good road conditions
    - 100 km/h for moderate road conditions
    - 80 km/h for poor road conditions
- **On the Finnish E18 site / 1998 Finland (implemented)**
    - Lowered from 100 to 80 km/h in winter
    - Lowered from 120 to 100 km/h in summer
    - Decreased both the mean speed and the standard deviation of speed
- **Along a 19-mile section of I-75 / 1993 Tennessee, USA (implemented)**
    - Lowered to 55 mph with fog warning sign
    - Lowered to 35 mph with fog warning sign
    - Close Interstate during extreme fog
    - 5 to 10 percent reduction in speed
    - no crashes due to fog after implementation

In summary, there are a number of existing algorithms based on different performance measures. For algorithms involving congestion mitigation or shockwave dampening, VSL signs are almost always associated with downstream detectors to decrease flow entering a congested area. Algorithms based on weather or road condition parameters usually deal with VSLs associated with adjacent detectors. In both cases it is most common to gradually lower the speed limit in increments of 5 or 10 mph. Most algorithms also use a safety measure that prevents adjacent signs from having more than a 10 mph difference between them. In addition, nearly all systems will use a mechanism to prevent hysteresis, or rapid fluctuation between displayed speeds. Some systems use minimum time durations, and others use reverse thresholds to avoid this event.

Types of VSL Sign Displays

There are several different types of variable speed limit signs utilized. The signs can be categorized into two groups: overhead signs and roadside signs. Either of these technologies can be accompanied by changeable message signs or flashing beacons displaying a “Reduced Speed When Flashing” message. This section provides a few examples of these two technologies.

In Seattle, Washington large overhead sign bridges (Figure A.2) display the variable speed limits. This is part of a system that can also display changeable messages and symbols. During normal conditions the speed limit is displayed on either side of the road, and overhead displays are blank. During reduced speed zones the speed is displayed above each lane and the roadside signs display “Reduced Speed Zone” messages (as shown in Figure A.2). The sign also has the ability to display lane closures and warn drivers of approaching congestion or incidents (WSDOT 2010).

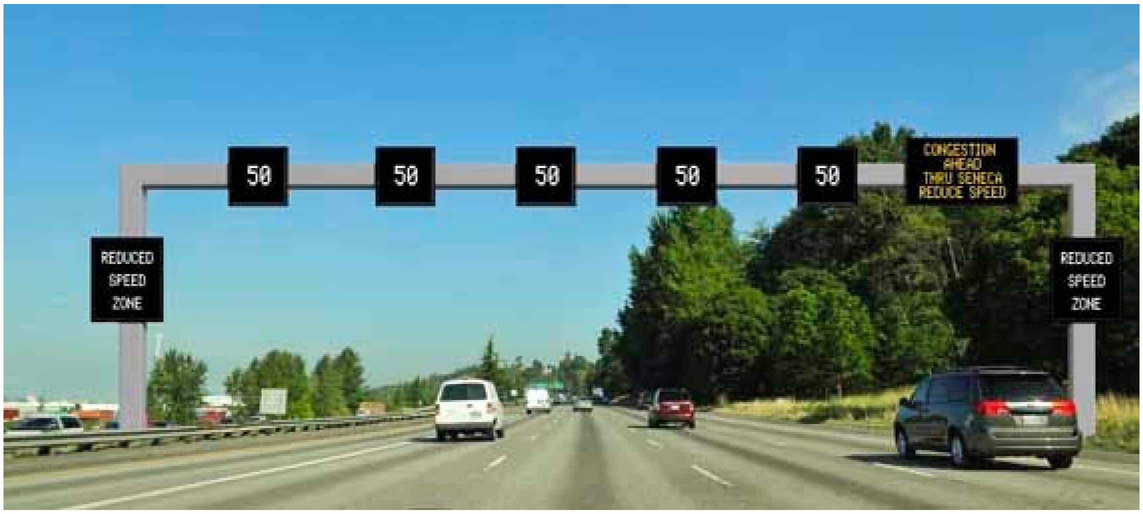


Figure A.2 VSL sign on I-5 in Seattle Washington (WSDOT 2010)

Similarly, the M25 in the United Kingdom also has an overhead variable speed limit display (Figure A.3). Each lane has a display of the reduced speed limit outlined by a red border to signify that it is enforceable. Automatic speed enforcement is also installed to capture vehicles violating the speed limit through photo-radar enforcement. This practice is prevalent throughout Europe and the technology for "fake" photo enforcement exists as well. In those cases a flash goes off when a vehicle is exceeding the speed limit, but no picture is taken. This makes the driver believe they have been issued a ticket (Robinson 2000).

Figure A.3 VSL Sign on M25 Motorway in the UK (Robinson 2000)

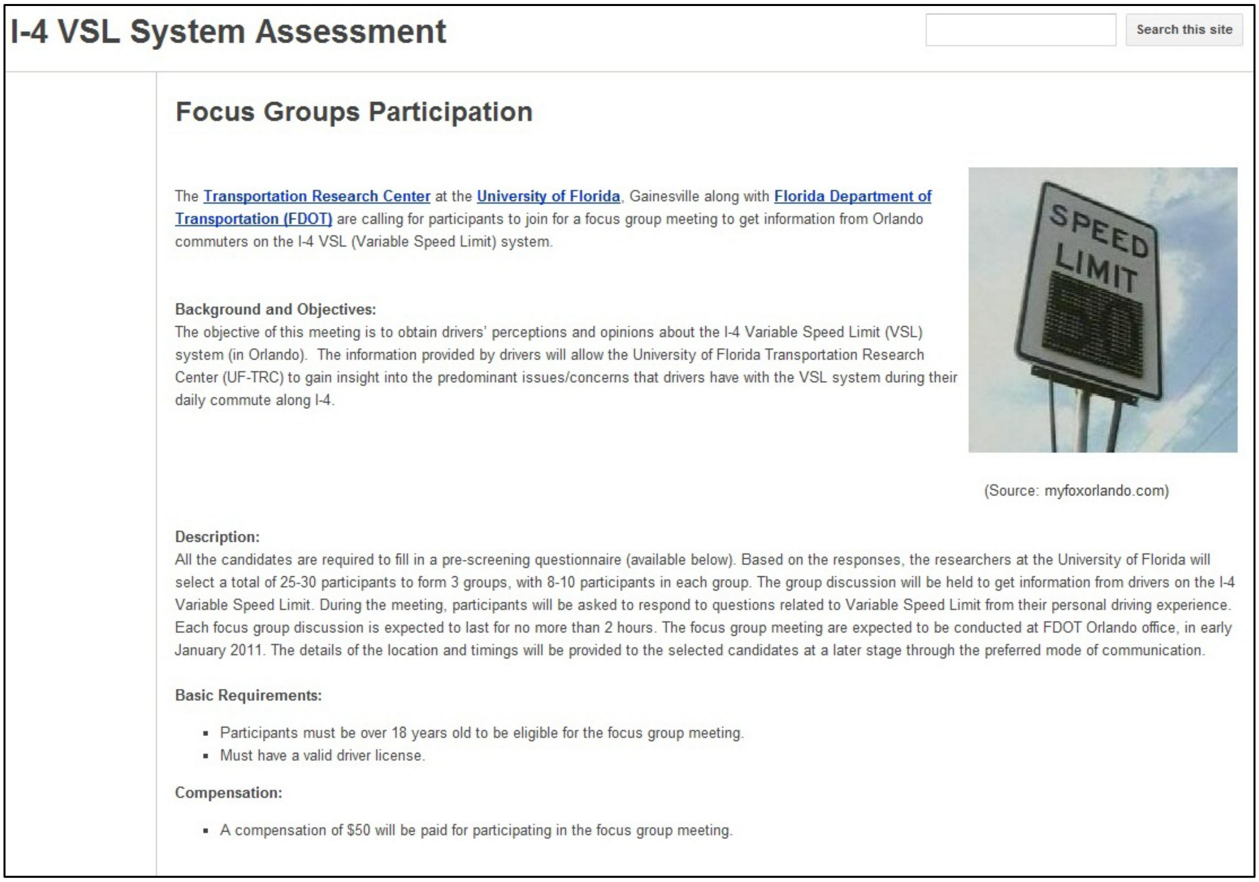
The variable speed limits used on I-4 in Orlando, Florida are displayed on LED illuminated roadside signs (Figure A.4). These signs employ a flashing beacon, and are designed to look similar to the surrounding static speed limit signs (Haas, 2009).

Figure A.4 Variable Speed Limit Sign on I-4 in Orlando, FL

Luoma and Rämä studied the effects of VSLs on speed behavior and memory of signs using two different sign technologies in southern Finland. They interviewed drivers after passing variable speed limit signs, and asked them if they could recall seeing the sign, and if so what the speed limit was. The two technologies were fiber-optic and electromechanical VSL signs. The study showed that fiber-optic signs had a significantly greater effect on speed reduction than the electromechanical signs. The fiber-optic signs also had a 91% recall where the electromechanical signs only had a recall of 71.6%. It should be noted that the average recall of fixed speed limit signs is 76 – 80%.

There has not been much direct comparison between types of signs, but the general consensus is that overhead signs are more visible than roadside signs. However the cost of building these overhead signs is significantly higher than that of roadside signs.

APPENDIX B – Focus Group Material



I-4 VSL System Assessment

Focus Groups Participation

The Transportation Research Center at the University of Florida, Gainesville along with Florida Department of Transportation (FDOT) are calling for participants to join for a focus group meeting to get information from Orlando commuters on the I-4 VSL (Variable Speed Limit) system.

Background and Objectives:
The objective of this meeting is to obtain drivers' perceptions and opinions about the I-4 Variable Speed Limit (VSL) system (in Orlando). The information provided by drivers will allow the University of Florida Transportation Research Center (UF-TRC) to gain insight into the predominant issues/concerns that drivers have with the VSL system during their daily commute along I-4.

(Source: myfoxorlando.com)

Description:
All the candidates are required to fill in a pre-screening questionnaire (available below). Based on the responses, the researchers at the University of Florida will select a total of 25-30 participants to form 3 groups, with 8-10 participants in each group. The group discussion will be held to get information from drivers on the I-4 Variable Speed Limit. During the meeting, participants will be asked to respond to questions related to Variable Speed Limit from their personal driving experience. Each focus group discussion is expected to last for no more than 2 hours. The focus group meeting are expected to be conducted at FDOT Orlando office, in early January 2011. The details of the location and timings will be provided to the selected candidates at a later stage through the preferred mode of communication.

Basic Requirements:

- Participants must be over 18 years old to be eligible for the focus group meeting.
- Must have a valid driver license.

Compensation:

- A compensation of $50 will be paid for participating in the focus group meeting.

Figure B.1 Snapshot of the advertisement in website/craigslist post

Table B.1 Socio-economic factors of the focus group participants by the respective groups

	Gender	Age	Group/Ethnicity	Marital	Children	Income Range	Drivers’Aggressiveness	Aware of VSL?	Round Trips on I-4 per week
Group 1	Male	35 to 45 y	Caucasian	Single	Yes	$60K to $80K	3	Yes	More than 9
	Female	25 to 35 y	Caucasian	Single	No	$20K to $40K	5	Yes	More than 9
	Male	45 to 55 y	Hispanic	Married	Yes	$60K to $80K	2	Yes	6 to 9
	Male	18 to 25 y	Asian	Single	No	Less than $20K	5	Yes	4 to 6
	Female	45 to 55 y	Caucasian	Divorced	Yes	$20K to $40K	5	No	6 to 9
	Female	18 to 25 y	Multi-race	Single	No	$20K to $40K	7	yes	6 to 9
Group 2	Female	25 to 35 y	Caucasian	Single	No	Less than $20K	4	Yes	4 to 6
	Male	25 to 35 y	Hispanic	Single	No	Less than $20K	5	Yes	More than 9
	Female	18 to 25 y	Hispanic	Single	No	Less than $20K	4	Yes	More than 9
	Male	35 to 45 y	Caucasian	Married	Yes	$20K to $40K	6	Yes	More than 9
	Female	18 to 25 y	African American	Single	No	Less than $20K	5	Not Sure	4 to 6
	Female	35 to 45 y	African American	Single	Yes	$20K to $40K	3	Yes	4 to 6
	Female	25 to 35 y	Caucasian	Single	No	$20K to $40K	3	Yes	More than 9
	Male	35 to 45 y	Caucasian	Married	No	$100K to $120K	5	No	More than 9
	Female	25 to 35 y	Caucasian	Single	No	$60K to $80K	3	Yes	More than 9
	Female	25 to 35 y	Caucasian	Single	Yes	Less than $20K	4	Not Sure	4 to 6
Group 3	Male	18 to 25 y	Asian	Single	No	$40K to $60K	4	Not Sure	4 to 6
	Male	25 to 35 y	Hispanic	Married	No	$60K to $80K	3	Yes	4 to 6
	Male	18 to 25 y	West Indian	Single	No	Less than $20K	5	Yes	1 to 3
	Male	25 to 35 y	Caucasian	Single	No	$40K to $60K	4	Yes	4 to 6
	Male	25 to 35 y	African American	Single	No	$20K to $40K	3	Yes	6 to 9
	Female	55 to 65 y	Caucasian	Married	Yes	Above $120K	4	Yes	6 to 9
	Female	45 to 55 y	Caucasian	Married	Yes	$20K to $40K	4	Yes	4 to 6
	Female	55 to 65 y	Caucasian	Single	No	$40K to $60K	3	Yes	4 to 6

I-4 VSL Assessment Focus Group Questions

Questions to be asked/discussed during all three focus groups sessions comprising of diverse pool of participants that are selected on the basis of socio-economic factors:

- What are the operating hours of the Variable Speed Limit system?
- While driving within the I-4 VSL zone, have you ever observed varying speed regulations being displayed? If not, Why?
- If you are driving within the VSL zone when the speed limit changes, what is your typical driving response?
- What effect do you think the VSL system has on your typical trip through the VSL zone?
- Do you know what purpose the VSL system is intended to serve?

Potential Other Follow-up Questions:

The following questions will be raised by the researchers during the focus group discussion, if necessary, depending on the discussion generated from the above questions.

- How often do you drive on I-4 per week? (in hours)
- Are you aware of the I-4 VSL (Variable Speed Limit) system?
- How often do you drive along the VSL zone?
- Do you think you will have a delay in your arrival time (at your destination) because of the VSL system?
- What are the major issues with the VSL system for you?
- Are the VSL sign boards on the side of the freeway visible to you?
    - If not, why can’t you see them?
    - Are the speed limits displayed on the boards visible from the “fast” lane?
- What measures should be taken so that you would follow the recommended speeds?
- Do you think the system is achieving its intended purpose?

Prescreening Questionnaire for I-4 Variable Speed Limit Focus Group Meetings

The University of Florida Transportation Research Center, along with the Florida Department of Transportation (FDOT), are calling for participants to join for a focus group meeting to get information from Orlando commuters on the I-4 VSL (Variable Speed Limit) system. A total of 25-30 participants are needed to form 3 focus groups, with 8-10 people in each group. Each group meeting is expected to last for 1.5 to 2 hours. Each participant will be paid $50 compensation for participating in the focus groups. The focus group meetings are expected to be held at the Orlando FDOT office on 12th March 2011.

The minimum eligibility requirements to participate in the focus group meetings are:
a) be at least 18 years of age
b) have a valid U.S. driving license
c) regularly drive along I-4 near downtown Orlando

If you meet these requirements and are interested in participating in the focus group meetings, please answer the questions on the following page. These questions will be used to select drivers with a wide range of backgrounds. Selected candidates will be informed of their confirmed participation by email or preferred mode of communication.

1) What is your gender?
   ○Male ○Female

2) What is your age range?
   ○18 to 25 years ○25 to 35 years ○35 to 45 years
   ○45 to 55 years ○55 to 65 years ○>65 years

3) Which of the following groups do you most identify yourself as?
   ○Caucasian ○Native American ○African American
   ○Hispanic ○Asian ○Pacific Islander ○Other

4) What is your marital status?
   ○Married ○Single ○Other

5) Do you have any children?
○Yes ○No

6) What is your occupation?

7) What is your annual income?
○Less than $20K ○$20K to $40K ○$40K to $60K
○$60K to $80K ○$80K to $100K ○$100K to $120K ○Above $120K

8) What type of driver do you consider yourself?

	1	2	3	4	5	6	7	
Extremely Conservative	○	○	○	○	○	○	○	Extremely Aggressive

9) How many round trips per week do you make on I-4?Between south of downtown district to north of downtown district

	0	1 to 3	4 to 6	6 to 9	More than 9
Round trips	○	○	○	○	○

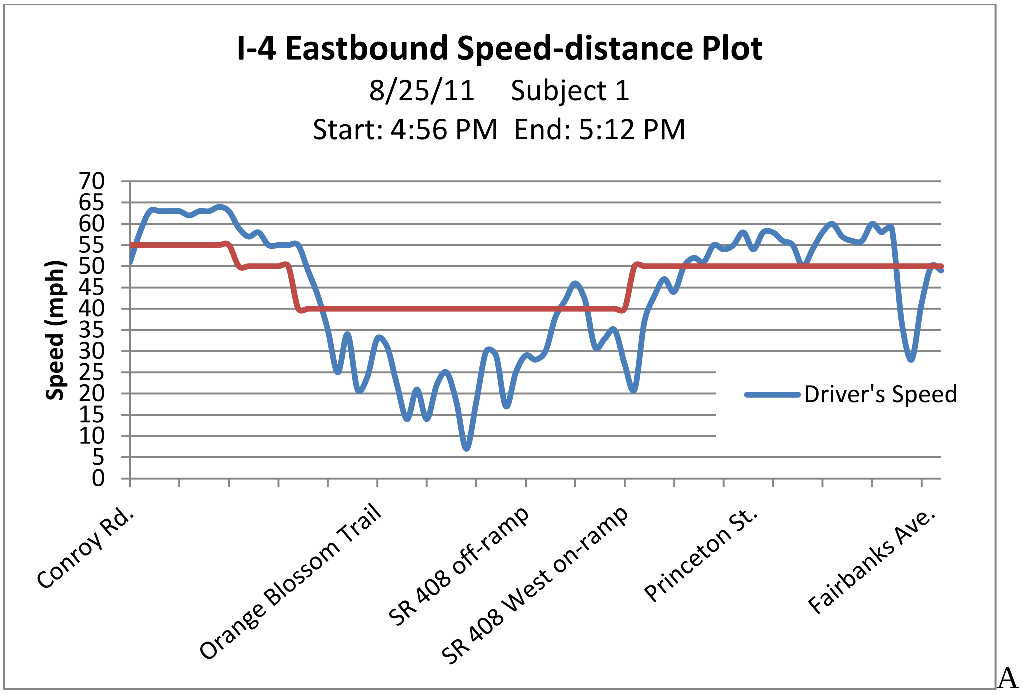
10) What times of day do you drive on I-4 ?Check all that apply
○AM Peak (6 AM to 9 AM) during workdays
○PM Peak (4 PM to 7 PM) during workdays
○Mid-day Peak (11 AM to 1 PM) during workdays
○Non-Peak hours (including holidays and weekends)

11) Are you aware of the I-4 VSL (Variable Speed Limit) system?
○Yes ○No

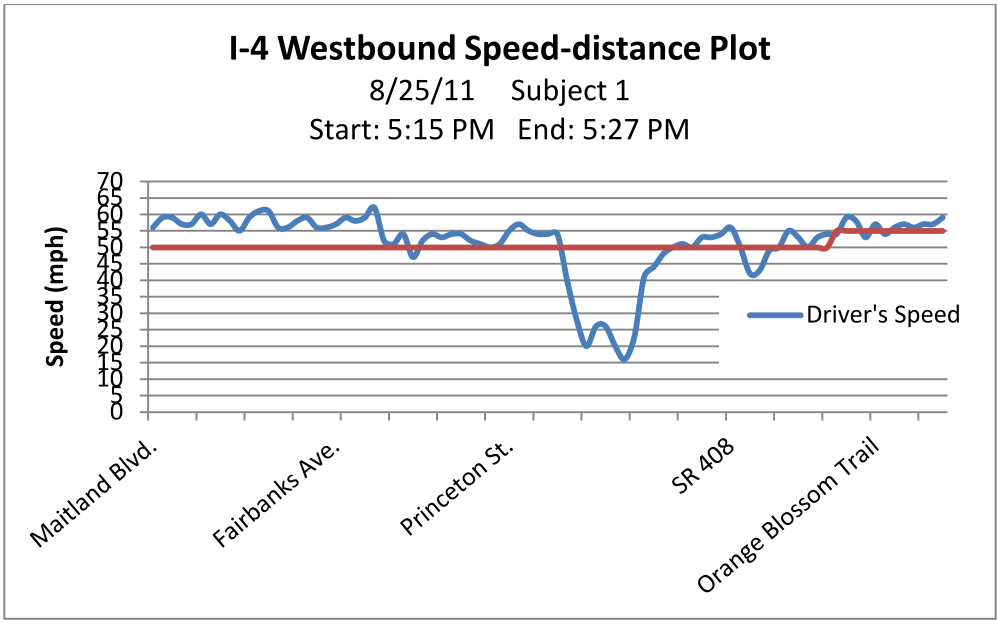
12) In general, do you have any comments on the I-4 VSL system?

13) Participants’ contact information (at least one from phone/email/mail)

APPENDIX C - Speed-Distance Plots for Each Individual Participant

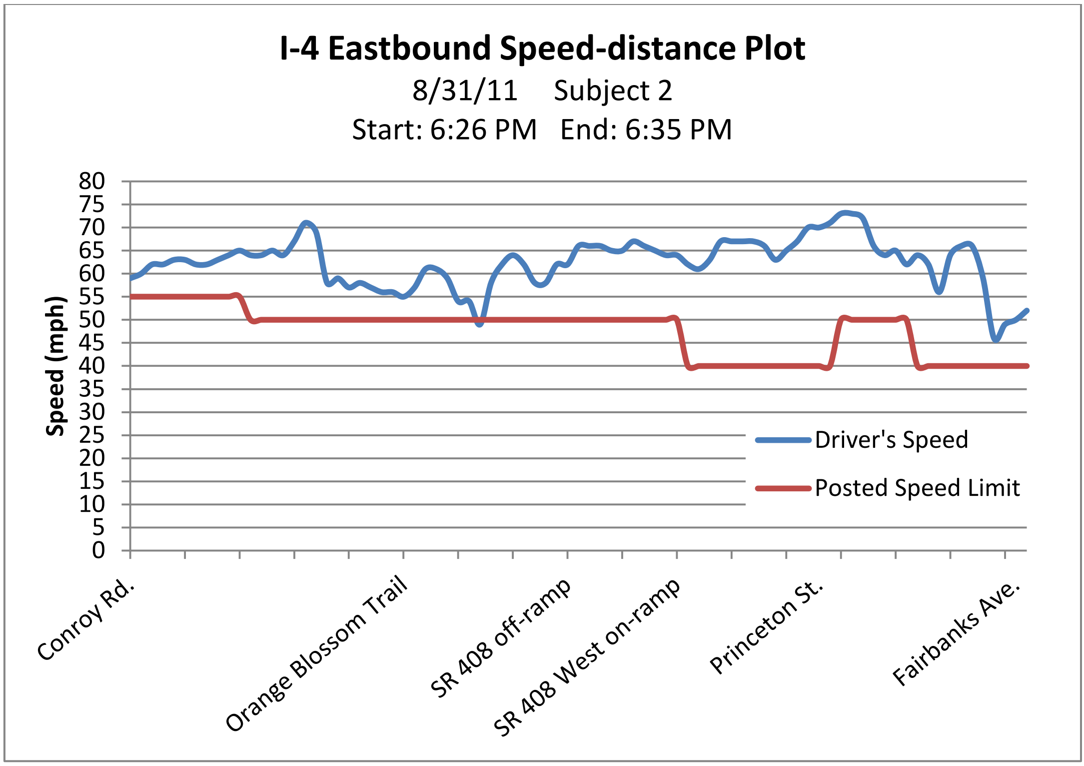


A

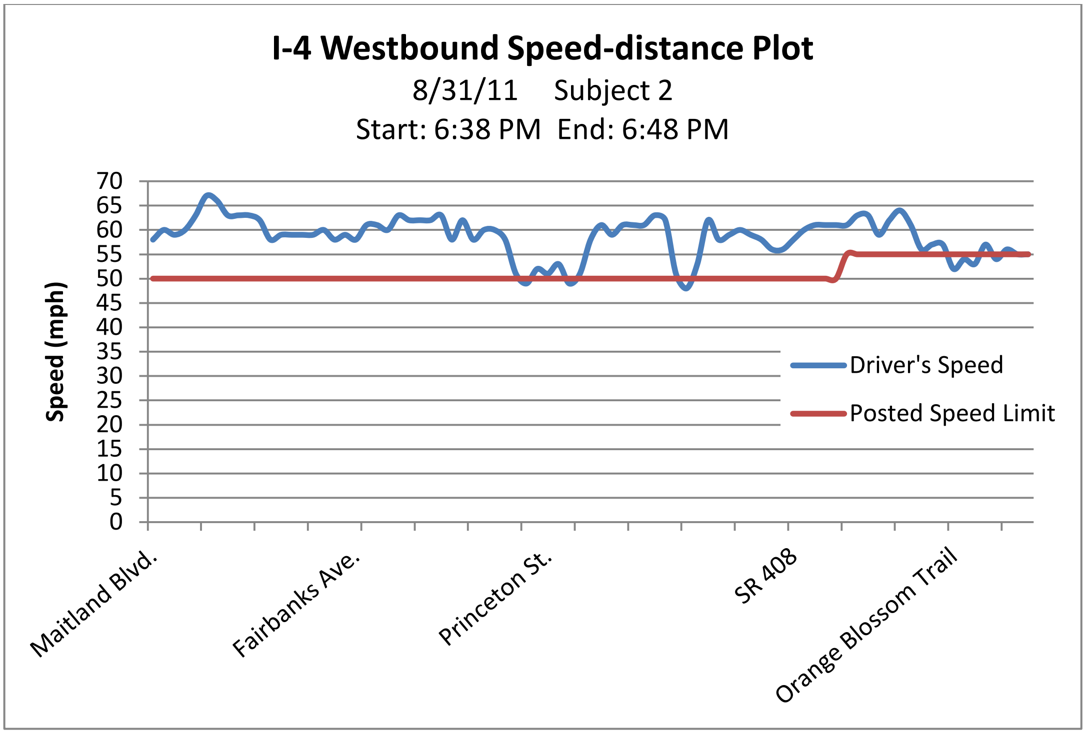


B

Figure C.1 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

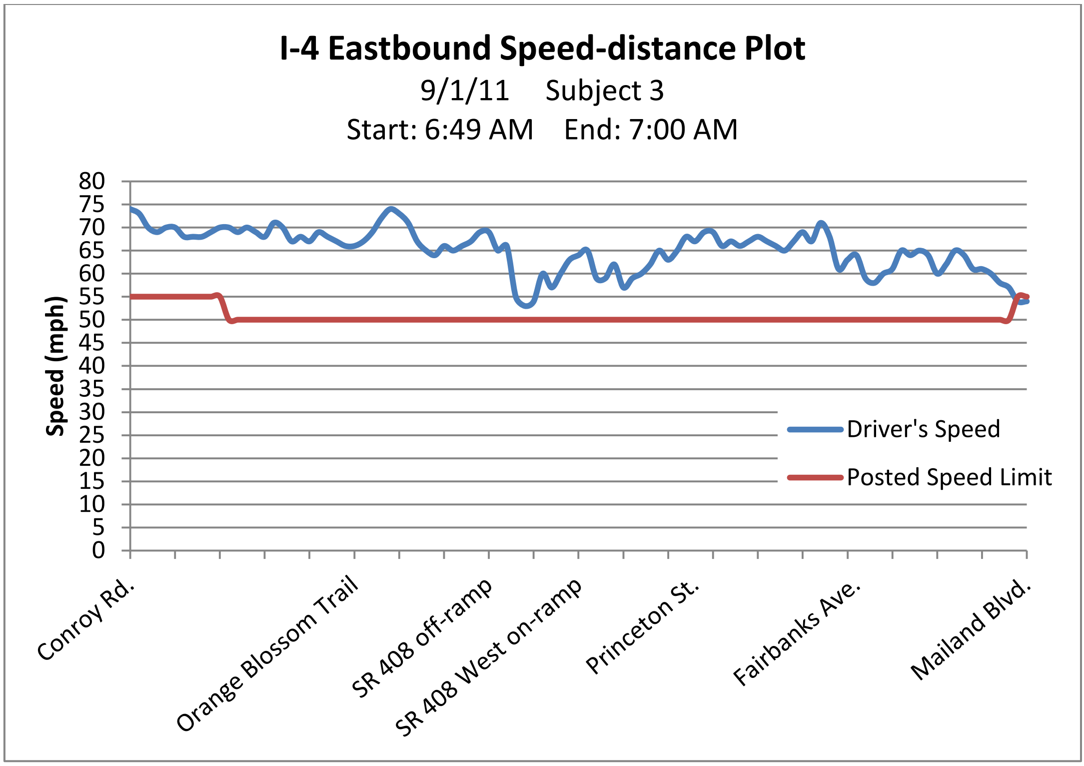


A



B

Figure C.2 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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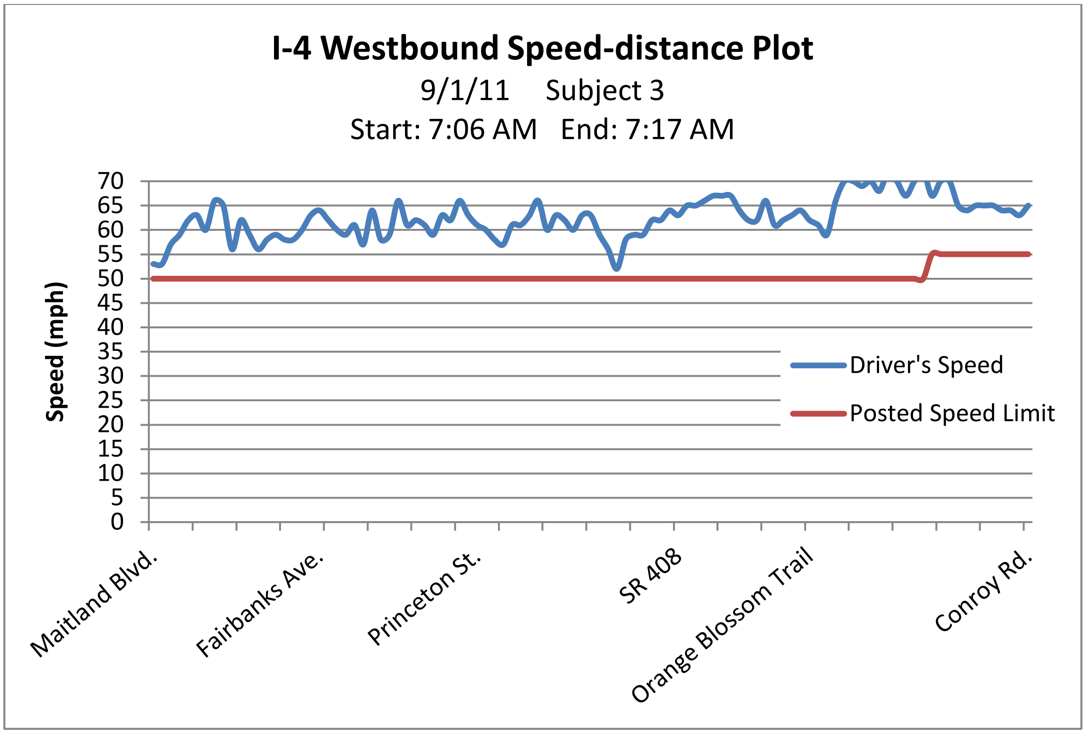


B

Figure C.3 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

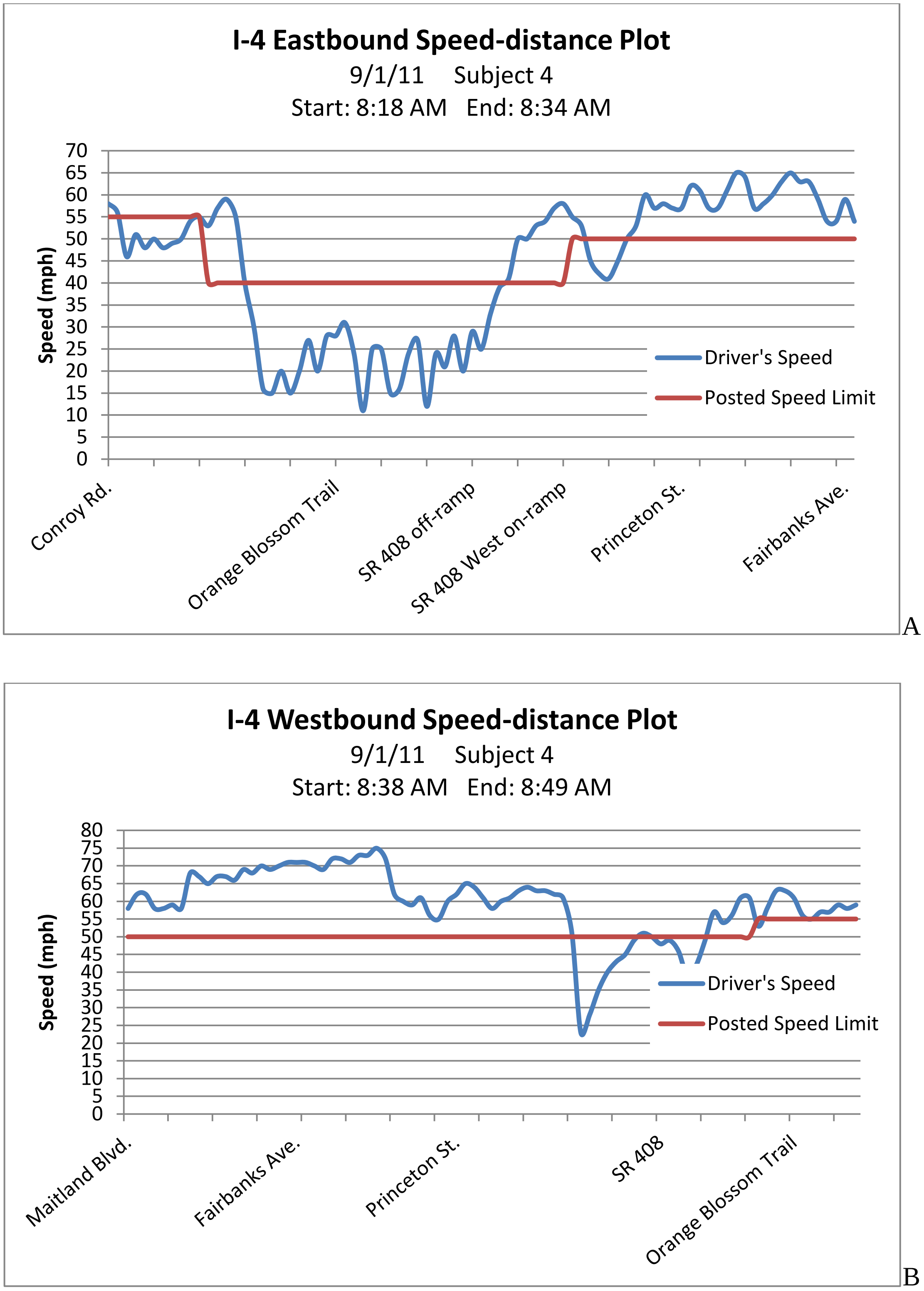
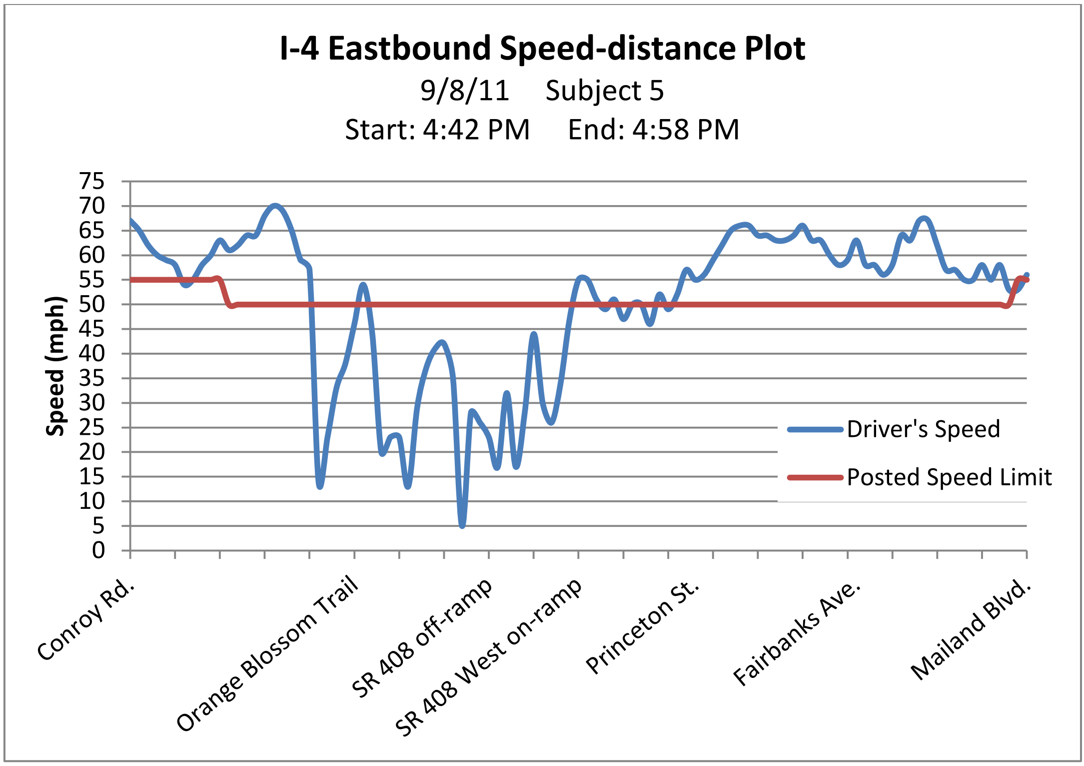


Figure C.4 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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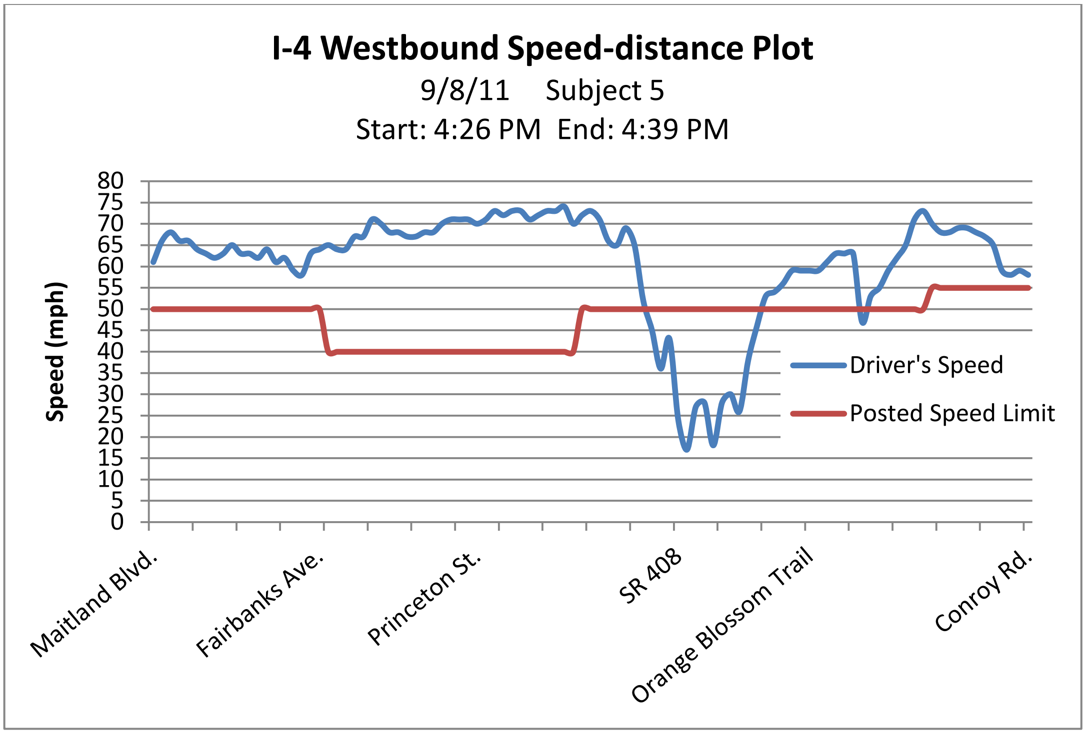
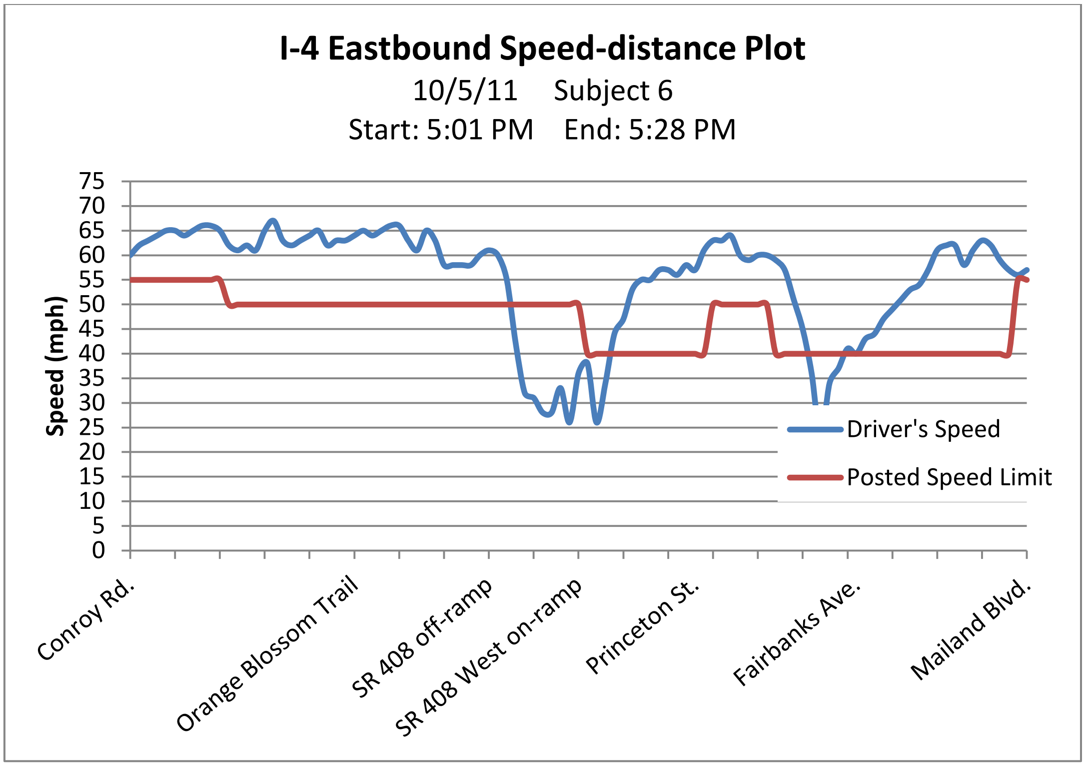


B

Figure C.5 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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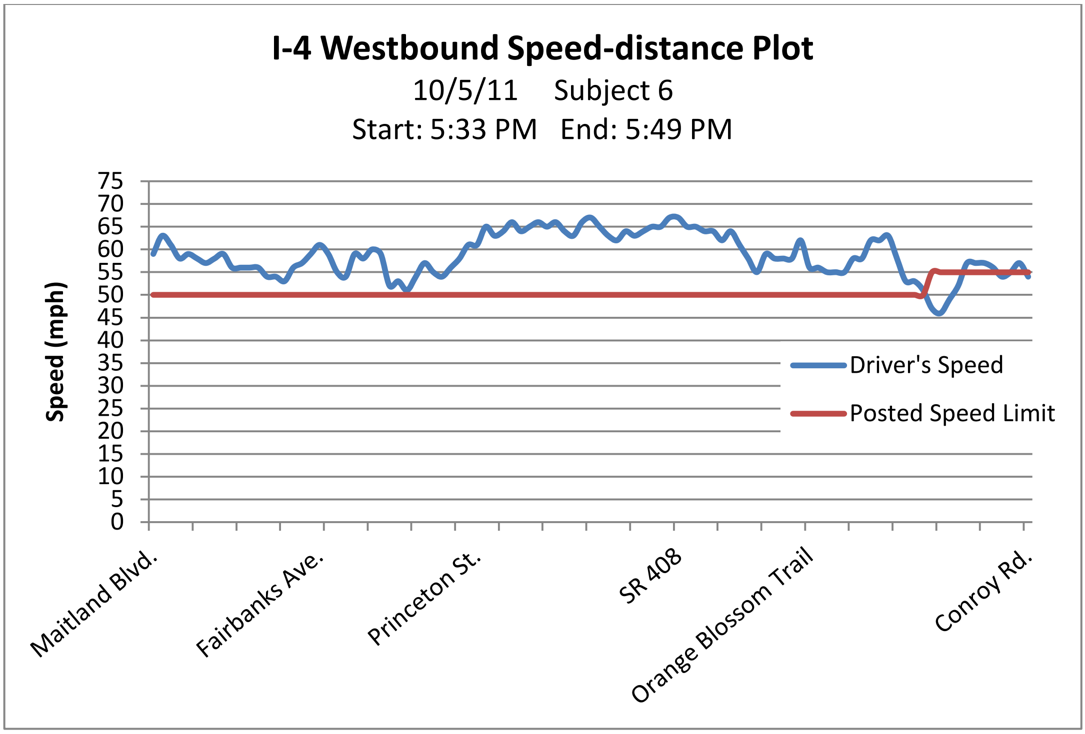


B

Figure C.6 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

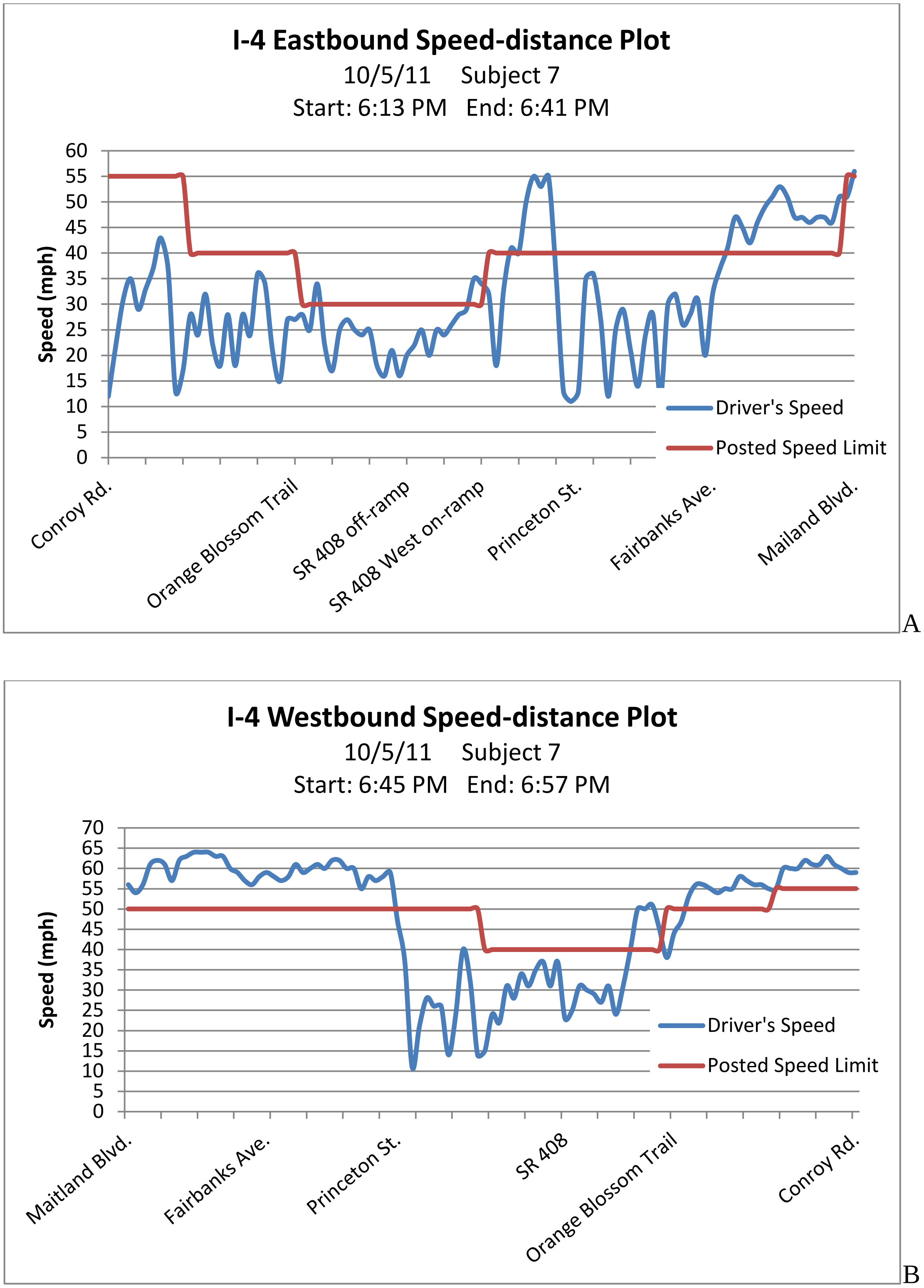


Figure C.7 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

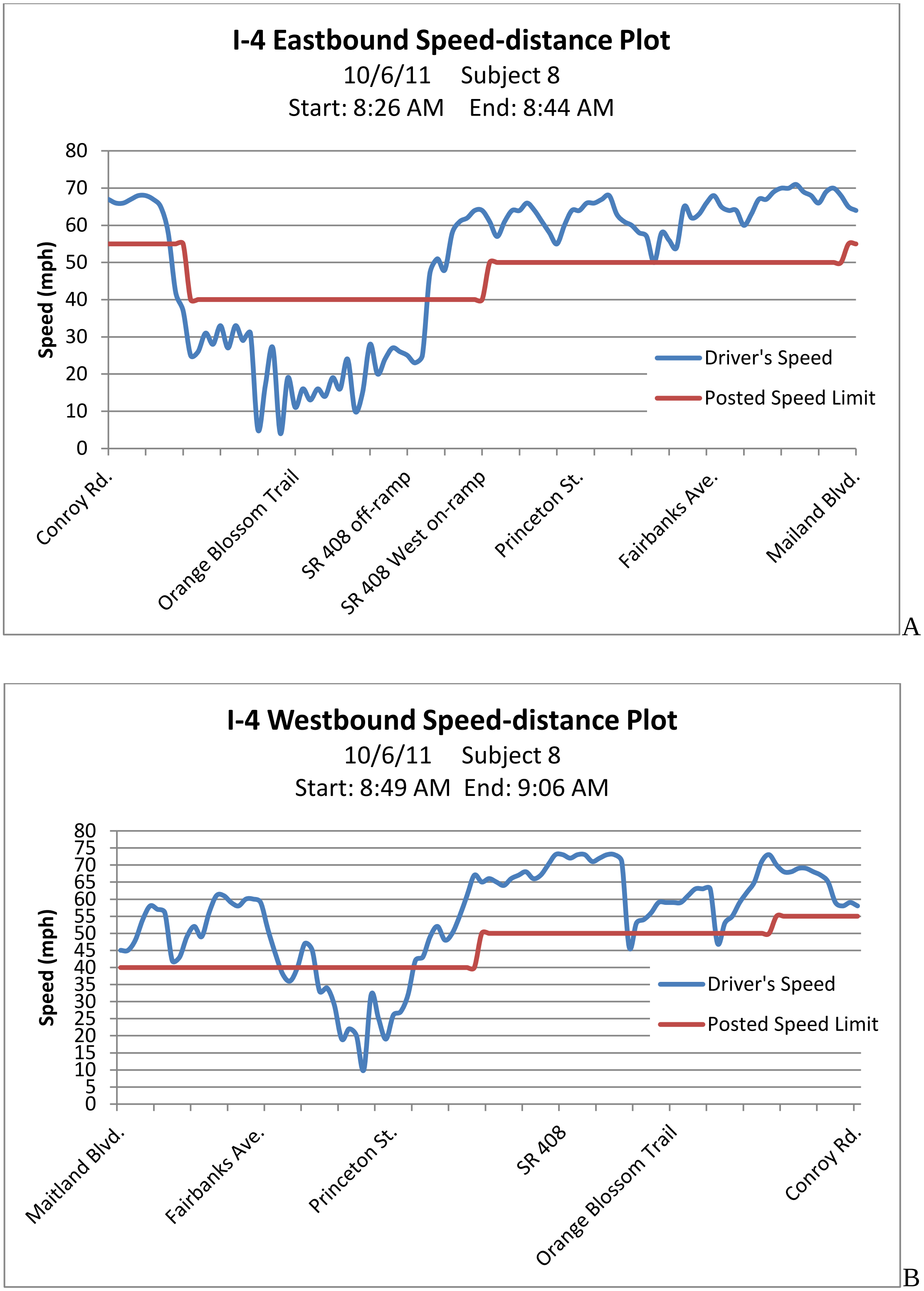


Figure C.8 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

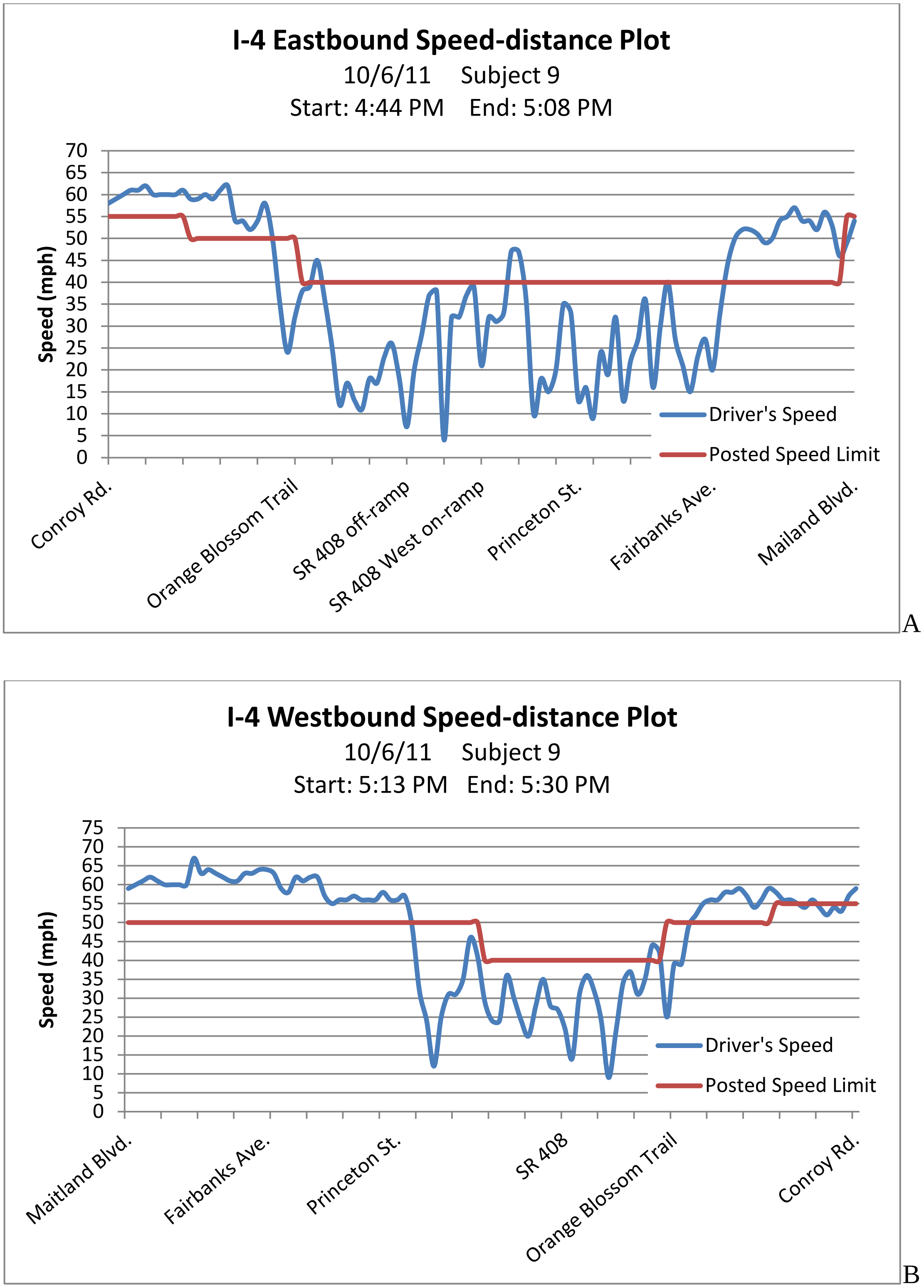
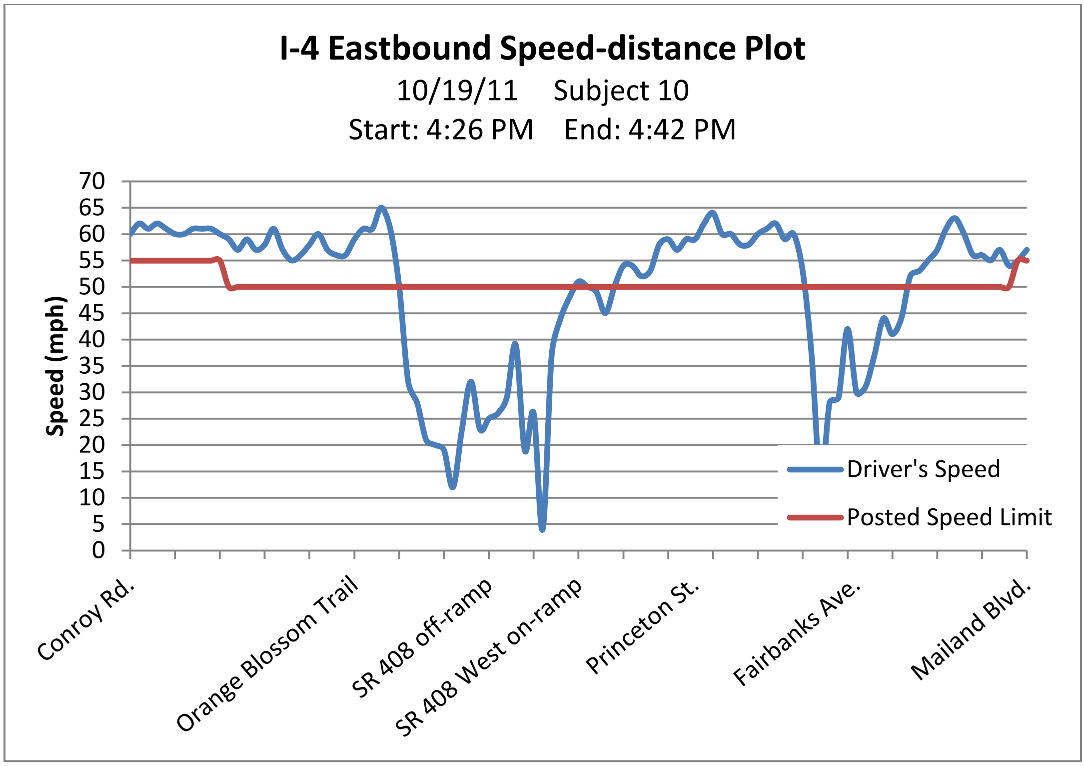


Figure C.9 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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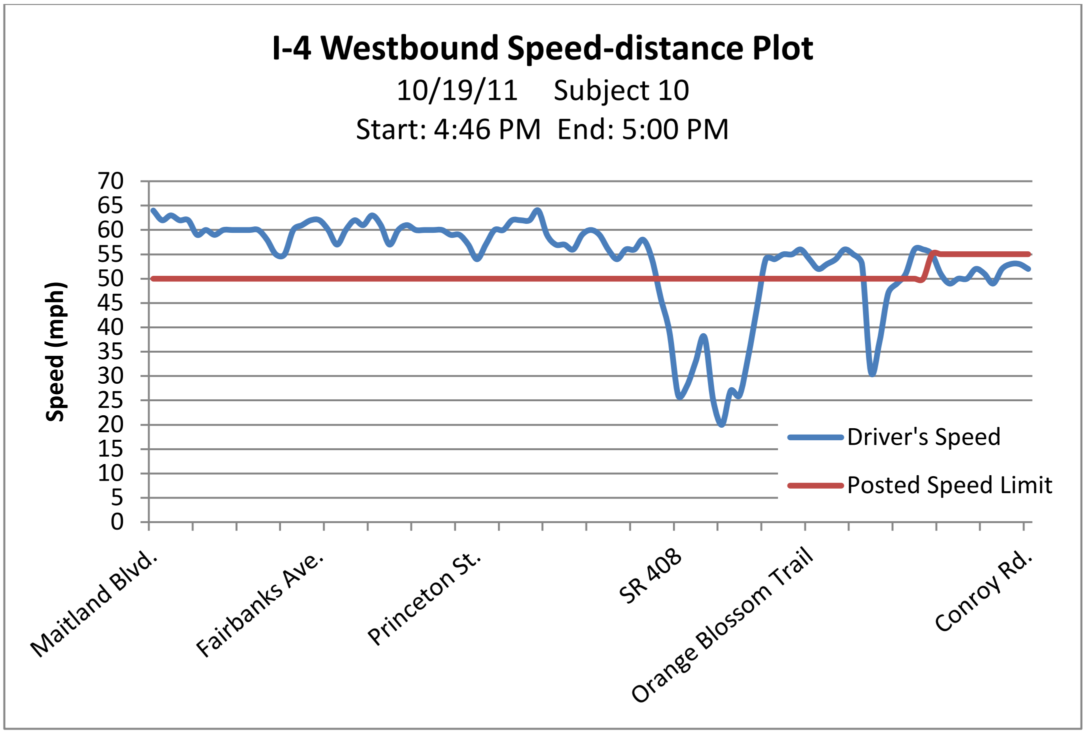
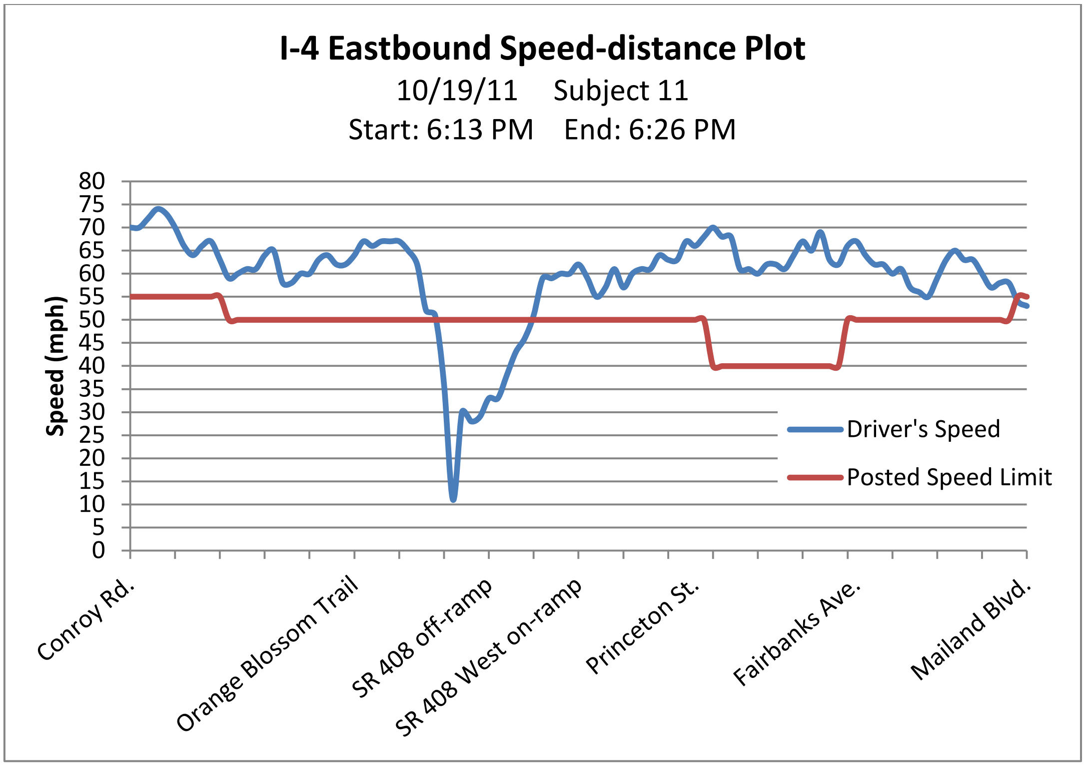


B

Figure C.10 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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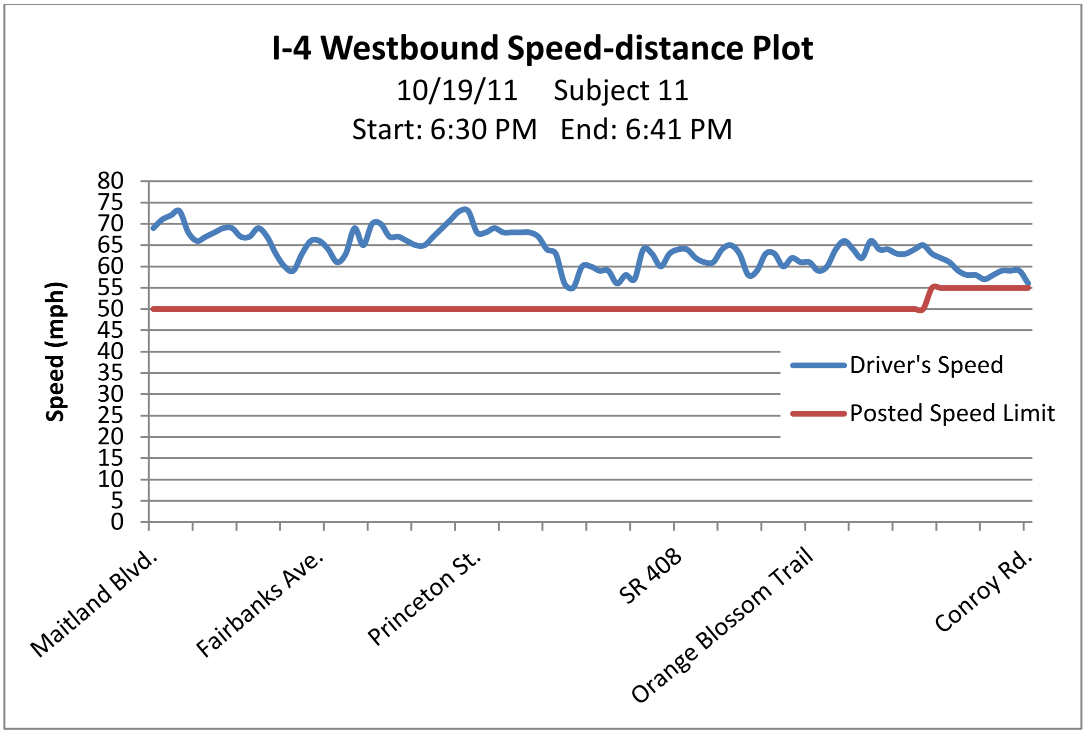
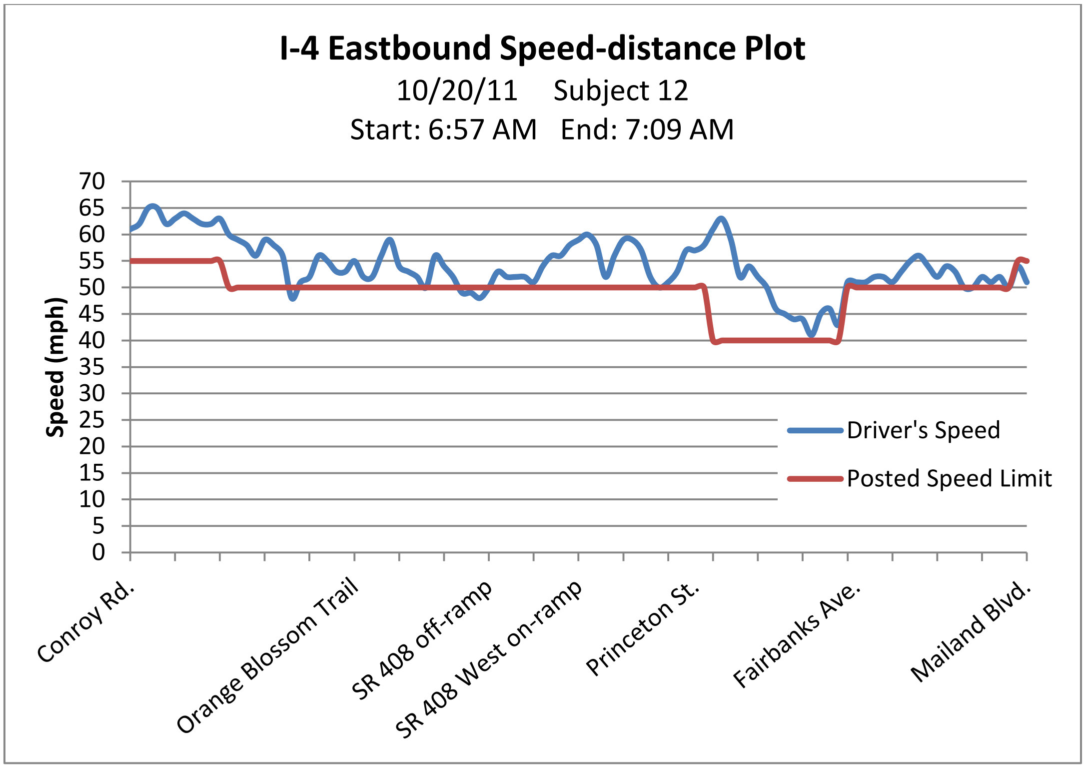


B

Figure C.11 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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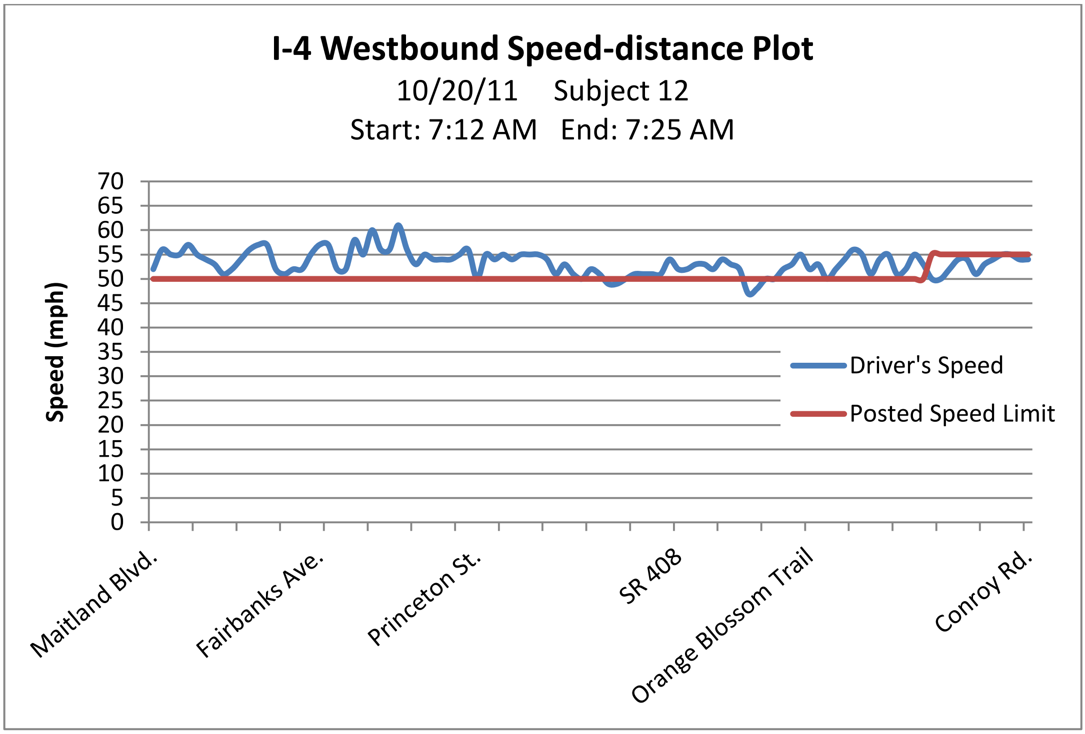
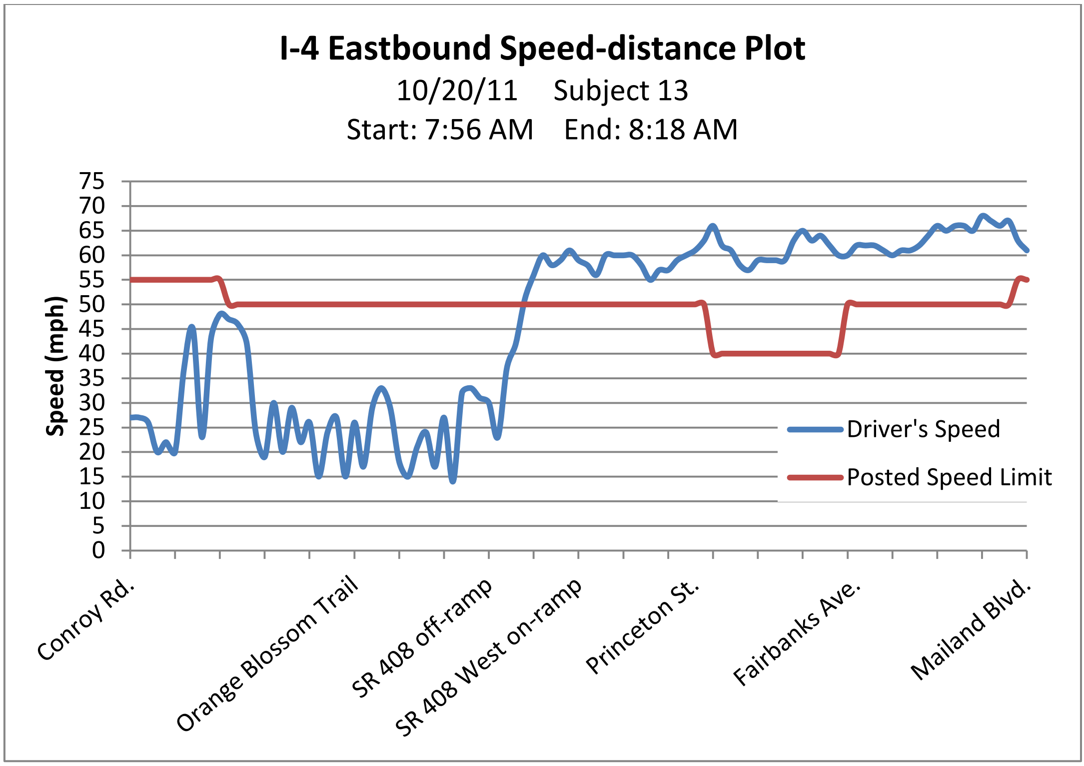


B

Figure C.12 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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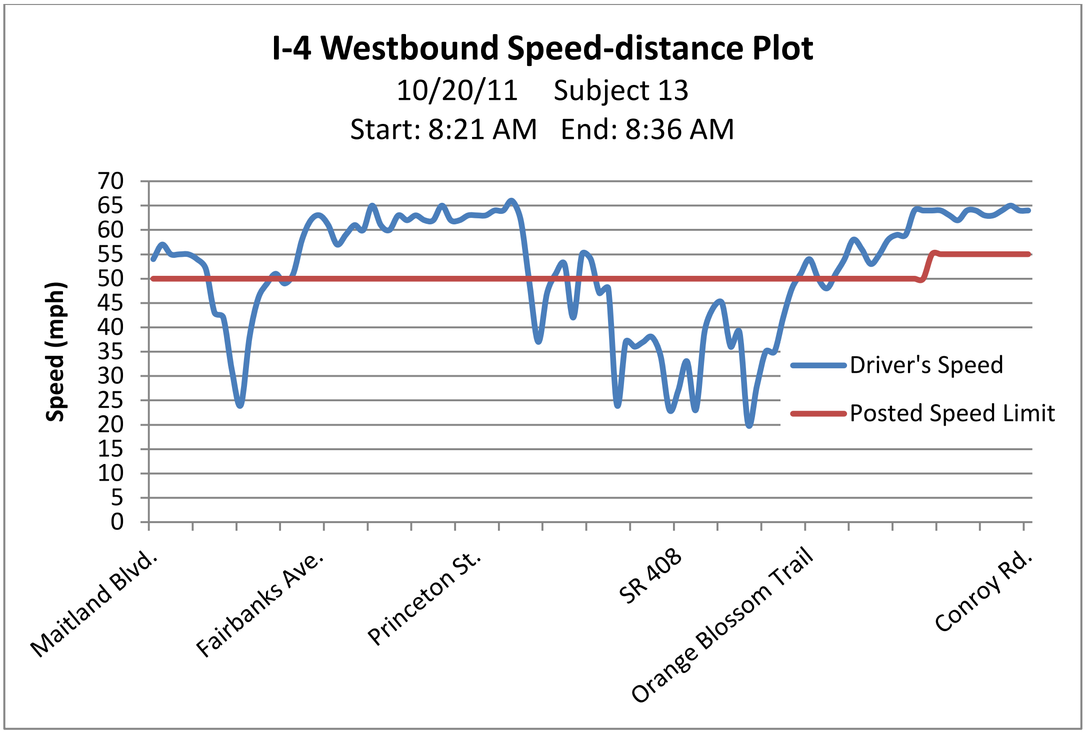
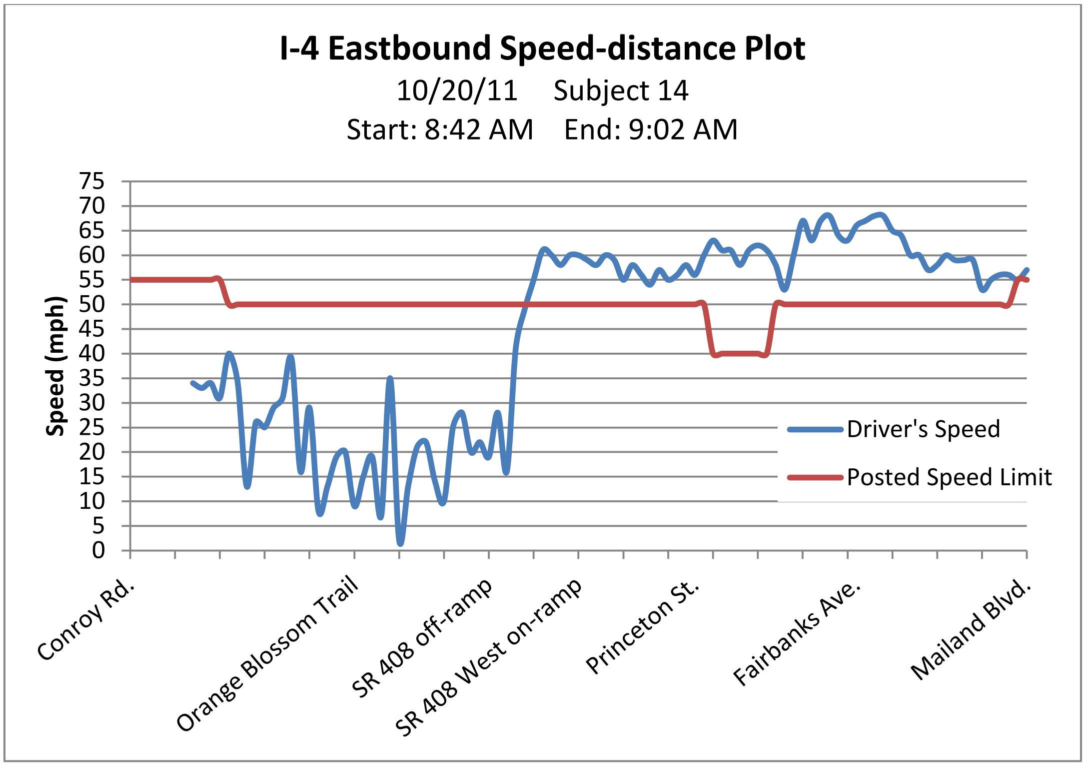


B

Figure C.13 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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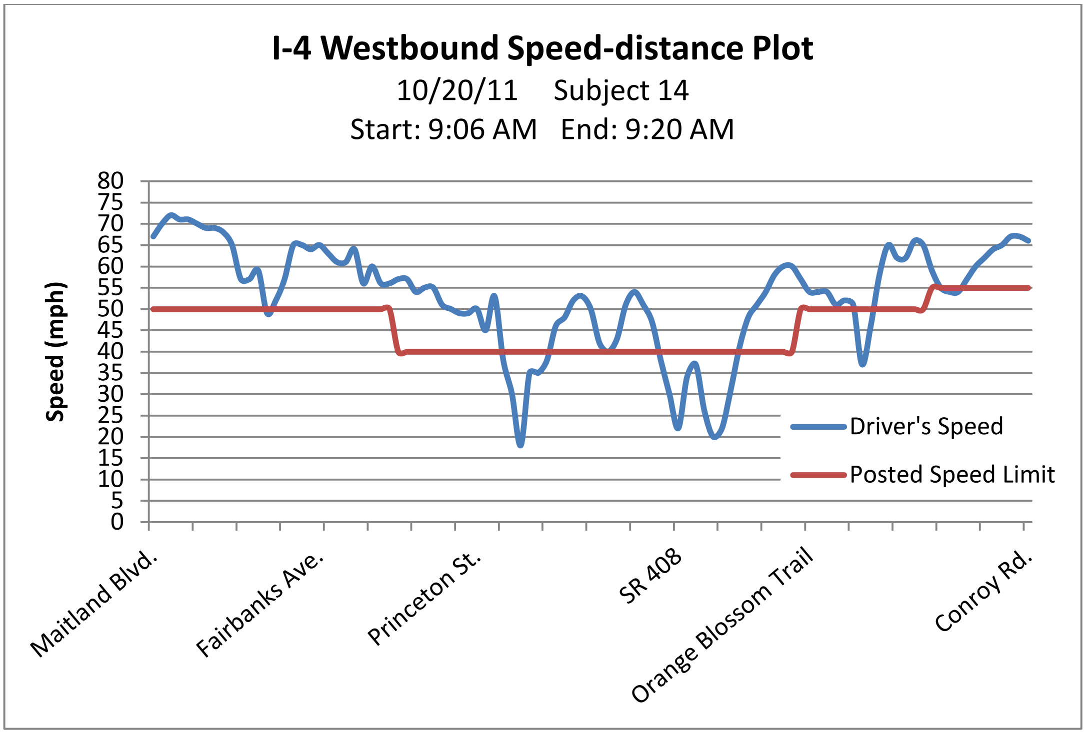
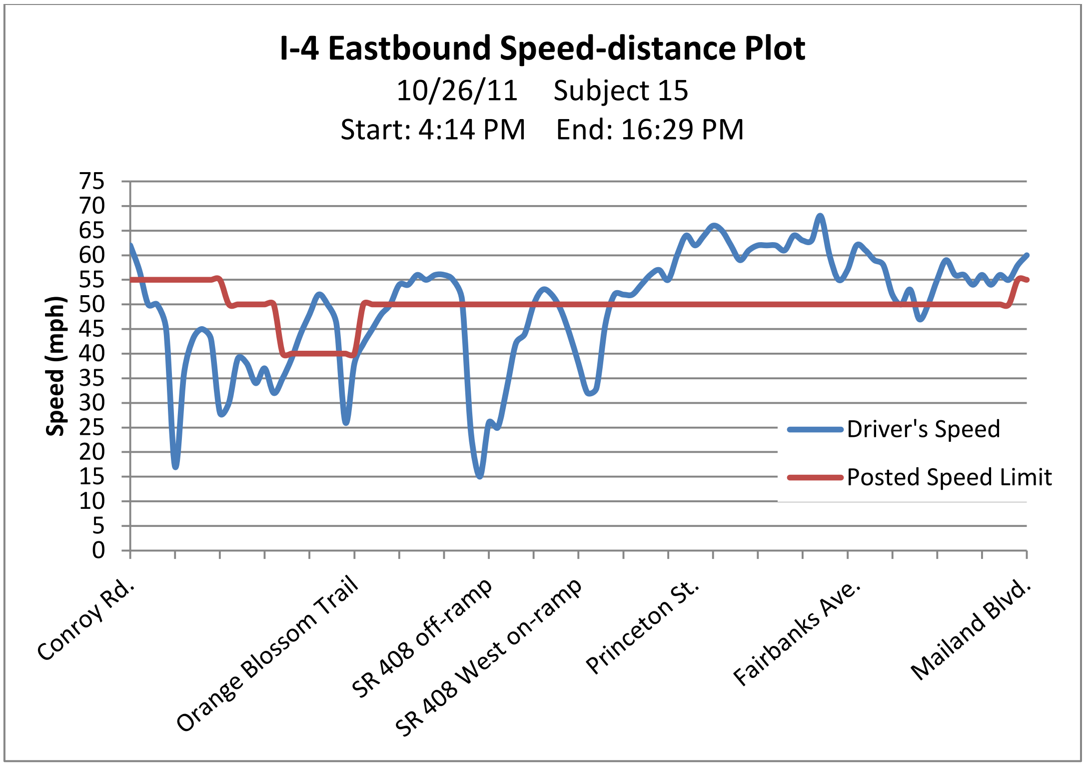


B

Figure C.14 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.



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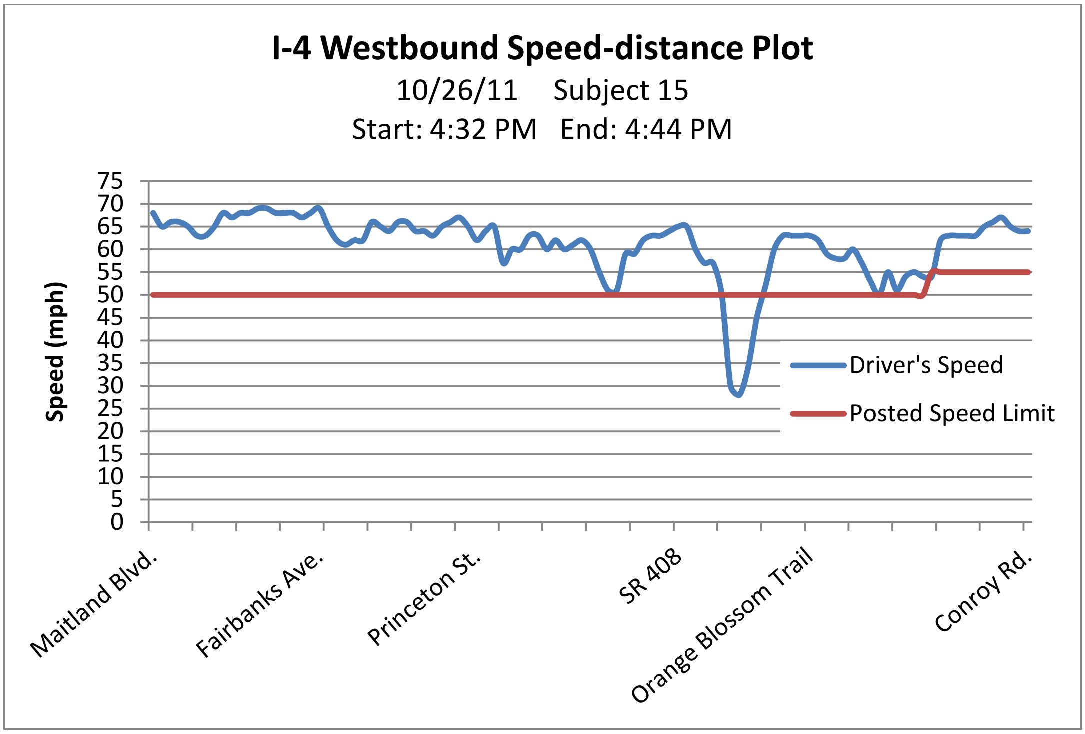

B

Figure C. 15 Speed of driver versus displayed speed limit over extent of VSL zone A) Eastbound Direction B) Westbound Direction.

APPENDIX D – Breakdown Identification

Table D.1 Comparisons of breakdown times for detectors inside the VSL zone W1

Months	Days	**VSL Zone W1 (Detectors ID's)**			
		At Lake Mary Blvd	At Lake Mary Off Ramp	West of Lake Mary	East of Lake Mary Rest Area
		511522	**511502**	**511482**	**511462**
November 2010	Day 1	7:09:00 AM	7:04:00 AM	**6:49:00 AM**	6:54:00 AM
	Day 2	7:09:00 AM	7:09:00 AM	**7:04:00 AM**	7:14:00 AM
	Day 3	7:29:00 AM	7:04:00 AM	**6:59:00 AM**	7:19:00 AM
	Day 4	7:34:00 AM	7:29:00 AM	**6:59:00 AM**	7:19:00 AM
January 2011	Day 1	7:09:00 AM	7:09:00 AM	**7:04:00 AM**	7:09:00 AM
	Day 2	7:29:00 AM	7:24:00 AM	**7:19:00 AM**	**7:19:00 AM**
	Day 3	7:34:00 AM	7:29:00 AM	**6:59:00 AM**	7:24:00 AM
	Day 4	7:24:00 AM	7:19:00 AM	**7:14:00 AM**	7:19:00 AM
	Day 5	9:19:00 AM	9:14:00 AM	**9:09:00 AM**	**9:09:00 AM**
	Day 6	6:49:00 AM	7:14:00 AM	**6:44:00 AM**	-
	Day 7	6:59:00 AM	6:39:00 AM	**6:34:00 AM**	6:39:00 AM
April 2011	Day 1	7:24:00 AM	7:19:00 AM	**6:59:00 AM**	7:24:00 AM
	Day 2	8:44:00 AM	8:44:00 AM	7:59:00 AM	**7:49:00 AM**
	Day 3	7:09:00 AM	7:09:00 AM	**6:49:00 AM**	7:04:00 AM
	Day 4	8:44:00 AM	8:39:00 AM	8:34:00 AM	**8:24:00 AM**

Table D.2 Comparisons of breakdown times for detectors inside the VSL zone E4 and E3

Months	Days	**VSL Zone E4 (Detector ID’s)**				**VSL Zone E3 (Detector ID’s)**		
		West of OBT/SR-441	At SR-441/OBT	At Michigan Ave	At Kaley Ave	At SR-408	At South St	At Robinson Ave
		510781	510791	510811	510831	510871	510891	510911
November 2010	Day 1	7:44:00 AM	7:49:00 AM	7:39:00 AM	7:34:00 AM	7:29:00 AM	7:29:00 AM	**7:24:00 AM**
	Day 2	7:49:00 AM	7:49:00 AM	7:39:00 AM	7:34:00 AM	7:29:00 AM	7:29:00 AM	**7:24:00 AM**
	Day 3	7:44:00 AM	7:44:00 AM	7:34:00 AM	7:34:00 AM	7:24:00 AM	7:24:00 AM	**7:19:00 AM**
	Day 4	7:44:00 AM	7:44:00 AM	7:34:00 AM	7:29:00 AM	7:24:00 AM	7:24:00 AM	**7:19:00 AM**
January 2011	Day 1	no congestion				7:39:00 AM	7:34:00 AM	**7:29:00 AM**
	Day 2	7:44:00 AM	7:59:00 AM	7:39:00 AM	7:34:00 AM	7:29:00 AM	**7:24:00 AM**	**7:24:00 AM**
	Day 3	no congestion				7:44:00 AM	**7:34:00 AM**	**7:34:00 AM**
	Day 4	no congestion				7:39:00 AM	**7:34:00 AM**	**7:34:00 AM**
	Day 5	7:49:00 AM	7:49:00 AM	7:44:00 AM	7:39:00 AM	7:39:00 AM	7:34:00 AM	**7:24:00 AM**
	Day 6	8:49:00 AM	8:49:00 AM	7:49:00 AM	7:44:00 AM	7:34:00 AM	7:29:00 AM	**7:24:00 AM**
	Day 7	no congestion		7:49:00 AM	7:44:00 AM	7:34:00 AM	**7:29:00 AM**	**7:29:00 AM**
April 2011	Day 1	8:09:00 AM	7:59:00 AM	7:44:00 AM	7:44:00 AM	7:34:00 AM	7:34:00 AM	**7:29:00 AM**
	Day 2	8:44:00 AM	8:44:00 AM	7:59:00 AM	7:49:00 AM	7:39:00 AM	**7:34:00 AM**	**7:34:00 AM**
	Day 3	7:49:00 AM	7:54:00 AM	7:39:00 AM	7:34:00 AM	7:29:00 AM	7:24:00 AM	**7:19:00 AM**
	Day 4	7:49:00 AM	7:54:00 AM	7:44:00 AM	7:39:00 AM	7:29:00 AM	**7:24:00 AM**	**7:24:00 AM**

APPENDIX E – Overview of Aerial Sessions

Aerial Session A1: Date: 04/13/2011, 7AM – 9AM

FDOT Personnel: Mr. Richard Morrow

Observations over I-4 EB:

- The I-4 EB corridor was found to be in free-flow during the early hours of the day between the roadways SR-435 and Maitland Blvd.
- Over the next half of the session, the I-4 EB corridor was found to be congested at the location where the on-ramp from SR-408 joins I-4. The merge operations at this location led to breakdown, causing the formation of long queues along I-4 EB further upstream.
- The queues built due to the merge operations at the on-ramp from SR-408 onto I-4 caused congestion further upstream till Kaley St. The off-ramp from I-4 towards Kaley St. was also found to be congested, probably due to high demand. Although not clearly evident, the queues built on this off-ramp also affected the traffic on I-4 mainline and therefore, may have also caused congestion further upstream till Orange Blossom Trail (OBT)/US-441.

Observations over I-4 WB:

- During the flight towards north of Orlando downtown, congestion began to appear on I-4 WB near the location where the on-ramp from Altamonte Springs (SR-436) joins I-4. This congestion was primarily observed over a lane drop with heavy incoming traffic from SR-436 onto I-4 WB. This congestion also led to queues formation further upstream till Lake Mary Blvd.
- During the second half of the session, congestion was still observed at sections where on-ramps from SR-436, and SR-434 joined I-4 because of the presence of a lane drop. However, the congestion appeared to dissipate at around 8:30 AM at these locations.

Aerial Session A2: Date: 04/13/2011, 4PM – 6PM

FDOT Personnel: Mr. Christopher Cairns

Observations over I-4 EB:

- During the first half of the aerial session, the section where the on-ramp from SR-408 joins I-4 EB was not found to be congested. But, during the second half of the session, queues appeared at this location.
- Long queues were observed on the lane leading to the off-ramp for SR-408 from I-4 EB. At that instant, it was interesting to note that all the other general-purpose lanes on the I-4 mainline were found to be free-flowing.
- Traffic congestion was observed at the section where the on-ramp from Fairbanks Ave joins I-4 EB. The heavy traffic from the on-ramp, along with the immediate horizontal terrain, was probably the primary reason for congestion along I-4.
- Traffic congestion was observed at the section where the on-ramp from Maitland Blvd joins I-4 EB. The on-ramp was fed with traffic coming from the right lane from Maitland Blvd WB, and the left lane turn from Maitland Blvd EB. The heavy on-ramp traffic appeared to cause friction at the merging location with I-4. This also led to the formation of long queues further upstream.
- During the last part of this session, the off-ramp towards Kaley St. was also found to be congested, and the queues built over this off-ramp appeared to have affected the I-4 mainline operations.

Observations over I-4 WB:

- Traffic congestion appeared at the lane leading to the off-ramp for SR-408 from I-4 WB. The congestion seemed to have affected the mainline operations, as long queues formed due to high demand for this off-ramp. The queue appeared to have propagated back to Ivanhoe Blvd and Colonial Dr. (SR-50).
- Long queues formed on the off-ramp leading to SR-50.
- It was interesting to note that few vehicles exited I-4 WB at the off-ramp for Ivanhoe Blvd but continued to travel along the off-ramp and joined back the I-4 mainline through the on-ramp from SR-50. In other words, the off-ramp, in general, was used as a by-pass to I-4 mainline.
- Long queue was observed over the lane leading to the off-ramp for Florida Turnpike. The long queue on this lane appeared to have blocked the traffic coming from Conroy Road onto I-4 WB.

Aerial Session A3: Date: 05/24/2011, 7AM – 9AM

FDOT Personnel: Mr. Jim Stroz

Observations over I-4 EB:

- During the early hours of the day (from 7AM – 7:20AM), free-flow conditions were observed along I-4 EB corridor. At around 7:30AM, congestion started to appear at the section where the on-ramp from SR-408 joins onto I-4 EB. The friction created by the merging vehicles resulted in formation of long queues further upstream till the off-ramp for SR-408 from I-4 EB, and even up to Kaley St. and Michigan Ave. The congestion at this location also led to the formation of long queues on SR-408 WB (the lane leading to the on-ramp for I-4).
- The off-ramp towards Amelia St. from I-4 EB was also found to be congested, and the queues appeared to have formed over the I-4 mainline. This affected the weaving movements of the vehicles between off-ramp towards Amelia St. and on-ramp from SR-408.
- Long queues were observed over the off-ramp towards Kaley St. from I-4 EB. The long queues appeared to have formed over the I-4 mainline as well, and affected the mainline operations. It may be possible that this off-ramp is short in length, and may be under capacity to handle high demand.
- Long queue appeared over the on-ramp from Maitland Blvd towards I-4 EB causing congestion at the merging point with I-4. The heavy traffic from the right-turn lane on Maitland Blvd WB, and the left-turn lane from Maitland Blvd EB appeared to join the on-ramp towards I-4 causing congestion.

Observations over I-4 WB:

- Long queues were observed over the off-ramp from I-4 WB to Ivanhoe Blvd. but it did not appear to have affected I-4 WB operations.
- The lane drop at the section where the on-ramp from SR-436 joins I-4 WB appeared to create friction, and caused congestion along I-4 corridor. It was observed that during the merge operations, the incoming vehicles from the on-ramps utilize the entire length of the acceleration lane to make a lane change instead of changing lanes at the first available gap. Similar observations were seen at the section where the on-ramp from SR-434 joins I-4 WB.
- The single lane off-ramp towards SR-434 from I-4 WB appeared to be used as double lane off-ramp. The high demand for this off-ramp probably explains this phenomenon.

Observations that vehicles were following the VSL system or the effect of VSL on easing the traffic congestion were not studied during this aerial session.

Aerial Session A4: Date: 05/24/2011, 3:30PM – 5:30PM

FDOT Personnel: Mr. Michael Sanders

Observations over I-4 EB:

- Long queues were observed on the lane leading to the off-ramp for SR-408 from I-4 EB. The queues appeared to have formed further upstream till Kaley St. During the last part of the session, the stretch of I-4 corridor from Kaley St. till CR-423/Conroy Road was found to be congested.
- The section where the on-ramp from SR-408 joins I-4 appeared to be congested due to merging activities. The congestion led to formation of queues further upstream. The downstream queue formed at the off-ramp for Amelia St. could also be one of the reasons for recurring congestion at this location.
- The section where the on-ramp from Maitland Blvd. joins I-4 appeared to be free-flowing first. However, during the second half of the session, the incoming traffic from the on-ramp from Maitland Blvd caused congestion at this location. It was interesting to note that long queues formed on Maitland Blvd on the right-turn lane from WB, and the left-turn lane from EB.
- Long queues were observed over the off-ramp to SR-436 (Altamonte Springs) from I-4 EB. The queues appeared to have affected I-4 mainline operations.
- The freeway section, east of SR-436 on I-4, appeared to be congested due to the presence of an emergency vehicle downstream. Moreover, the incoming traffic joining I-4 from the SR-436 on-ramp caused further congestion.
- The section where the on-ramp from Lee Rd joins I-4 EB was found to be congested. The merging vehicles propelled the friction over I-4, and the resulted shockwave was observed to travel upstream at Fairbanks Ave. Also, the incoming traffic from the on-ramp at Fairbanks Ave. on-ramp, along with the horizontal terrain seems to have congested the I-4 corridor. Although the downstream of this location was found to be congested, the speed limit on the VSL sign board appeared to be 50 mph.

Observations over I-4 WB:

- Long queues were observed over the off-ramp for SR-408 entrance from I-4 WB. The queue appeared to have affected I-4 mainline operations as well.
- The lane leading to the on-ramp for Florida Turnpike appeared to be congested, and slow moving.

Aerial Session A5: Date: 05/25/2011, 6:30AM – 8:30AM

FDOT Personnel: Mr. Christopher Cairns

Observations over I-4 WB:

- During the early hours of the session, 7AM – 7:20AM, free flowing conditions were observed along the I-4 corridor from Orange Blossom Trail (OBT) to Maitland Blvd in both EB/WB directions.
- At the sections where the on-ramps from Lake Mary Blvd and SR-434 join I-4 WB, congestion was not observed. However, due to increasing incoming traffic from these on-ramps, friction did begin between the vehicles near the lane drop. The section, downstream of the lane drop appeared to be free-flowing.
- The section where the on-ramp from SR-436 joins I-4 WB appeared to be congested. The lane drop at this location is the primary cause for this observation. During the remainder of the flight session, this section did not appear to be free-flowing again. The congestion led to the formation of queues further upstream till SR-434. It is interesting to note that the immediate downstream of this location was under free-flowing conditions throughout the flight session.
- The traffic was under free-flow condition at the freeway section west of Maitland Blvd on I-4 WB.
- The Exit Only lane for Lee Rd. from I-4 WB appeared to have high demand, but this section was never found to be congested. All the other general-purpose lanes at this location were found to be free-flowing.
- The sections where the on-ramps from Fairbanks Ave towards I-4 EB and WB were never found to be under congested situations.
- Long queues were observed over the off-ramp towards Princeton St. but it did not affect the I-4 mainline operations.

Aerial Session A6: Date: 05/25/2011, 3:30PM – 5:30PM

FDOT Personnel: Mr. Michael Smith

Observations over I-4 EB:

- Early in the session, congestion appeared at the location where the on-ramp from SR-408 joins I-4 EB. The queues built from this congestion resulted in congestion further upstream till OBT.
- The off-ramps from I-4 EB and I-4 WB for SR-408 were found to merge before leading onto SR-408. It appeared that the merge operations at this location slowed the traffic, and resulted in formation of long queues over both off-ramps. The queues on the off-ramps eventually led to congestion over the I-4 mainline as well. At this location, it appeared that the demand for SR-408 EB on-ramp is significantly higher than the on-ramp for SR-408 WB.
- The speed limit at Rio Grande Ave appeared to be 50 mph, even when downstream section was found to be congested. After a while, the speed limits appeared to drop to 40 mph at the same location. At that instant, the vehicles and the traffic may have slowed down in response to a lower posted speed limit. But it is not clearly evident if the average speeds on I-4 were decreased due to changing speed limits because the right lanes were moving faster than the left lanes.
- The speed limit was found to be 40 mph at OBT, when the downstream section was congested.
- The speed limit was found to be 40 mph at the location east of Kaley St., when congestion was observed at downstream section.
- At Ivanhoe Blvd, speed limits appeared to be 50 mph and it was observed that the vehicles were slowing down near the VSL sign board. The presence of a horizontal terrain could be the primary reason for this observation. However, after the passing the speed limit sign board, the vehicles appeared to have regained their speeds.
- The transition from free-flowing conditions to congested conditions was captured during the aerial session at the section where the on-ramp from Maitland Blvd joins I-4 EB. The traffic from Maitland Blvd on-ramp appeared to have caused congestion along I-4 mainline.

Observations over I-4 WB:

- Long queues were found over the off-ramp towards SR-408 from I-4 WB. The queues appeared to have resulted in congestion along I-4 corridor as well.

Aerial Session A7: Date: 05/26/2011, 6:30AM – 8:30 AM

FDOT Personnel: Ms. Angela Wilhelm

Observations over I-4 EB:

- During the early hours of the day, free-flowing conditions were observed along I-4 EB and WB directions.
- The section where the on-ramp from SR-408 merges with I-4 was found to be congested and the congestion resulted in formation of long queues upstream. During the second half of the session, it was observed that the queues were formed further upstream till Kaley St.
- Long queues appeared to have formed over off-ramp towards Kaley St. and it also appeared to have affected the I-4 mainline operations. Further upstream of Kaley St., the traffic queues were found to be dissipating faster on the outside lanes as compared to the inside lanes. At that instant, the VSL sign indicated speed limit as 30 mph, but it is not clearly evident if the speed limits were followed by the vehicles. However, even if the vehicles followed the speed limits, the congestion along I-4 did not appear to dissipate.

Observations over I-4 WB:

- The section where the on-ramp from SR-436 joins I-4 was not found to be congested during the early hours of the day. However, with increasing incoming traffic from the on-ramp, congestion started to appear at the merge point of the on-ramp with I-4. At that instant, the downstream location was not congested, but the friction created by the merging vehicles appeared to have congested the upstream section of I-4 towards SR-434.
- The section where the on-ramp from Maitland Blvd joins I-4 WB was not found to be congested.
- With the merging vehicles from Lee Rd onto I-4 WB, friction was developed along I-4 corridor but it did not result in congestion.
- Long queues were formed over the off-ramp for Princeton St. indicating that the high demand for this ramp.
- At the section west of Ivanhoe Blvd, the inside lanes of I-4 were slower as compared to the outside lanes of I-4. The vehicles used the exit lane at Ivanhoe to by-pass I-4 mainline traffic, and joined the I-4 mainline back at section east of SR-50.
- It appeared that the trucks over the I-4 mainline propelled slow-and-go type traffic along the corridor, and caused shockwaves.
- Long queues were observed over the off-ramp from SR-408 WB to join I-4 WB.
- The queue built over the off-ramp towards Michigan St. was also found to have affected I-4 mainline operations.

Aerial Session A8: Date: 05/26/2011, 3:30 PM – 5:30PM

FDOT Personnel: Mr. Richard Morrow

Observations over I-4 EB:

- The off-ramp towards Kaley St. was found to be congested, and the queues built over it appeared to have affected the I-4 mainline operations.
- The lane leading to the off-ramp for SR-408 was found to be congested. This led to the formation of the queues along I-4 further upstream causing congestion till Kaley St. At this location, it appeared that the outside lanes were dissipating faster than the inside lanes. Interestingly, the fourth general-purpose lane, or the lane next to the auxiliary lane was mostly under-utilized. It appeared that several vehicles chose not to be a part of long queues, and preferred to take the off-ramp at the gore junction. In other words, these vehicles blocked the fourth general-purpose lane of I-4 corridor to make way for the off-ramp, and therefore resulted in capacity reduction.
- The off-ramps for SR-408 from I-4 EB and WB were found to merge before leading onto SR-408. The merging vehicles at this location appeared to have created friction that led to formation of queues along I-4 mainline. Also, the demand for the on-ramp onto SR-408 EB was found to be more than the demand for the on-ramp onto SR-408 WB.
- It was observed that the queues built over the off-ramp for Kaley St. affected the I-4 mainline operations, and probably propelled the formation of queues upstream till OBT. At this instant, it was observed that the vehicles were joining the downstream congestion, and it indicated that the speed limit posted on the VSL sign board was not followed.
- The section where the on-ramp from SR-408 joins I-4 EB was found to be congested.

Observations over I-4 WB:

- The off-ramp to SR-408 from I-4 WB appeared to be congested. During the first half session, only the right most general-purpose lane was congested due to the queue spillback from the off-ramp. However, at a later time, all the other general-purpose lanes appeared to be congested as well. The congestion at this location led to the formation of queues further upstream till Ivanhoe Blvd. At this instant, the vehicles appeared to slow down at the point near the VSL sign board. It is however not clear, if the reduced posted speed limits resulted in reduced vehicular speeds.

Aerial Session A9: Date: 06/07/2011, 3:30PM – 5:30PM

FDOT Personnel: Mr. Christopher Cairns

Observations over I-4 EB:

- At first, the off-ramp towards Kaley St. did not appear to be congested. But at a later time, as the demand for the off-ramp increased, it appeared to be congested. The queue built over the off-ramp appeared to have affected I-4 mainline operations as well.
- The off-ramp towards SR-408 appeared to be congested, and the right most lane of I-4 mainline was found to be congested. At the same time, all the other three general-purpose lanes were found to be free-flowing.
- The section where the off-ramps from I-4 EB and WB merge before leading onto SR-408, was found to be congested. It was observed that the demand for the SR-408 EB on-ramp was more than the demand for the SR-408 WB.
- The high demand over the on-ramp from SR-50 to I-4 appeared to have caused friction on I-4 mainline resulting in formation of queues up to Amelia St.
- The VSL sign board at Ivanhoe Blvd indicated a speed limit of 50 mph. At that instant, the vehicles appeared to slow down. However, it is not clear if the vehicles reduced their speeds because of the displayed speed limit.
- The section where the on-ramp from Maitland Blvd joins I-4 did not appear to have congestion at first. But, at a later time, this location was found to be congested with increasing incoming traffic from Maitland Blvd. This resulted in formation of queues over I-4 further upstream till Lee Rd and Fairbanks Ave.
- Vehicles appeared to slow down after crossing the Fairbanks Ave. but this may be attributed to the horizontal terrain of I-4, not necessarily reduced speed limits.

Observations over I-4 WB:

- Long queues were formed over the off-ramp for SR-408 from I-4 WB, and resulted in congestion along I-4 mainline. At that instant, the VSL sign board at Ivanhoe Blvd displayed a speed limit of 40 mph, but it was clearly visible that the vehicles were not slowing down. In other words, the vehicles were joining the downstream queues, and the VSL signs did not appear to ease the traffic condition.

Aerial Session A10: Date: 06/08/2011, 6:30AM – 8:30AM

FDOT Personnel: Mr. Jeremy Dilmore

Observations over I-4 EB:

- During the early hours of the session i.e., from 6:45AM to 7:15AM, the section where the on-ramp from SR-408 merges with I-4 was not found to be congested. However, between 7:30AM and 8:00AM, this section was found to be congested. The weaving movements were found to be affected due to the merging vehicles from SR-408, and the vehicles exiting I-4 through the Amelia St. off-ramp.
- The traffic congestion at the section where the on-ramp from SR-408 joins I-4 resulted in formation of long queues further upstream along I-4.
- The off-ramp for Kaley St. appeared to have high demand, and the formation of queues over this ramp led to traffic congestion along I-4 mainline as well.
- Even though the VSL sign board at the location downstream of Kaley St. was flashing a speed limit of 40 mph (indicating downstream congestion), the vehicles did not appear to have slowed down.

Observations over I-4 WB:

- Traffic congestion was observed at the locations where the on-ramps from SR-436 and SR-434 join I-4. The queues at the section west of SR-436 appeared to have formed further upstream till SR-434. The traffic congestion at these locations continued to appear during the second half of the session as well.
- The in-coming traffic from Maitland Blvd on-ramp appeared to create friction along I-4 WB, and led to formation of queues further upstream.
- The off-ramp to SR-50 appears to have high demand during the second half of the session.

APPENDIX F – Calibration Results for Speed and Volume

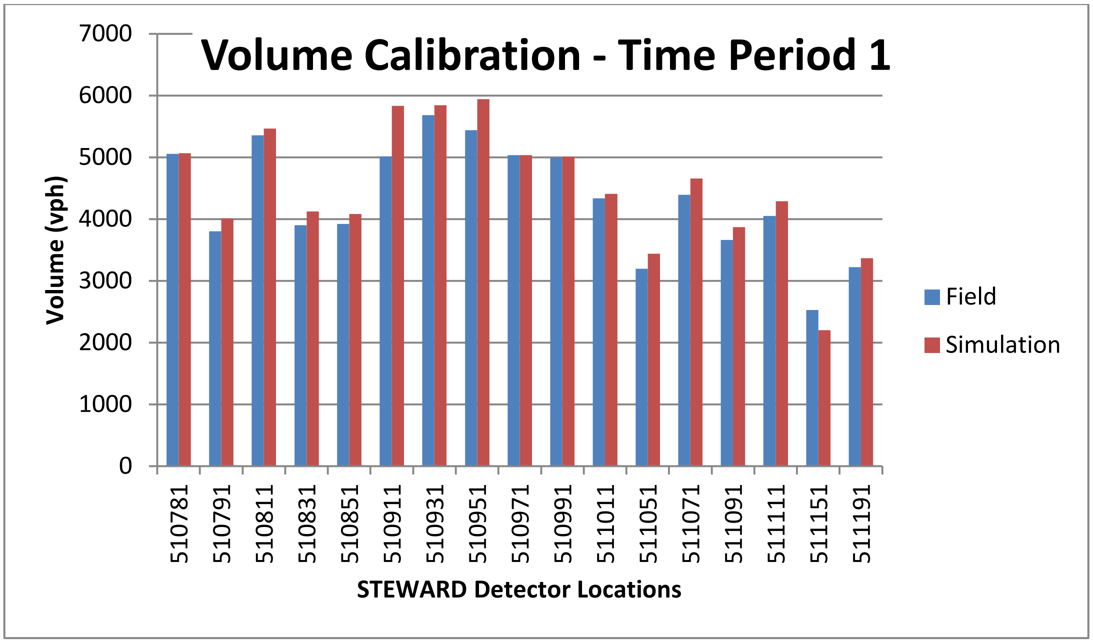

Figure F.1 Comparison between simulation volumes and field volumes for Time Period 1

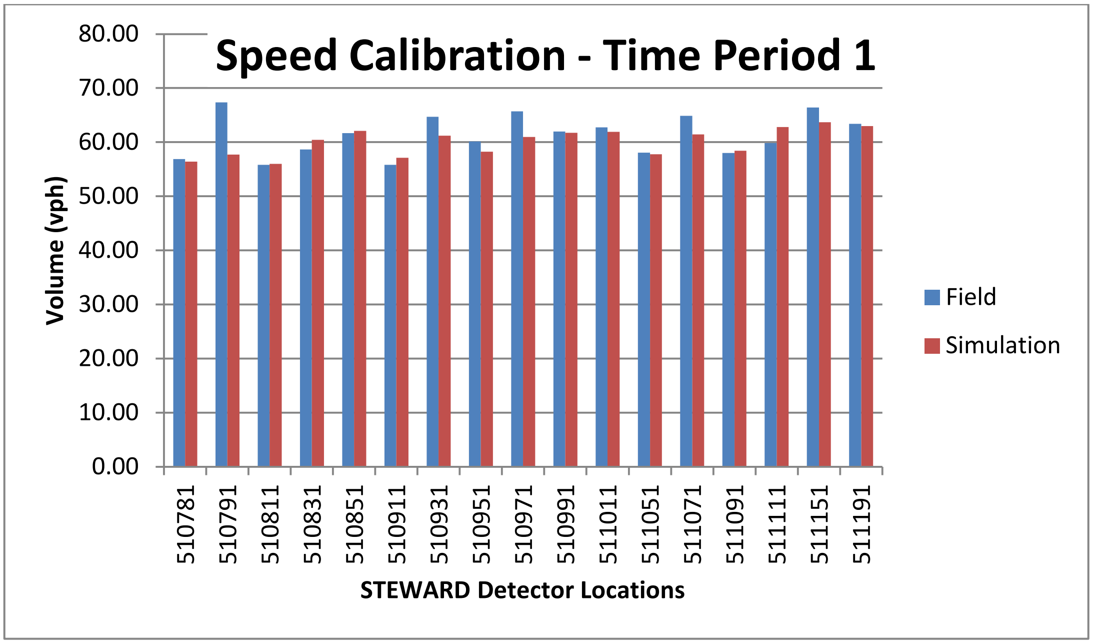

Figure F.2 Comparison between simulation speeds and field speeds for Time Period 1

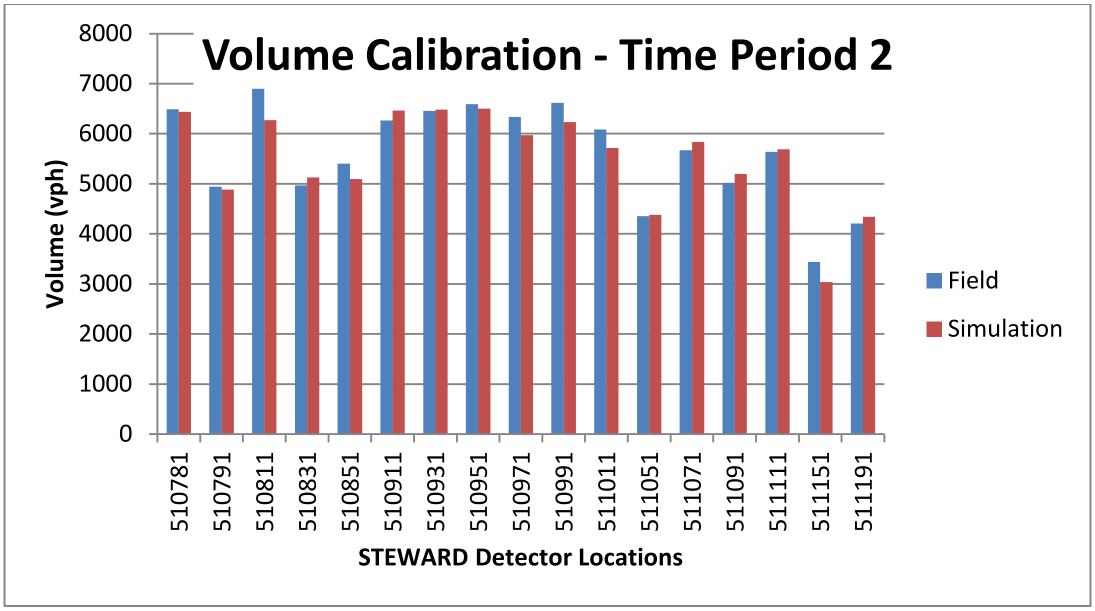

Figure F.3 Comparison between simulation volumes and field volumes for Time Period 2

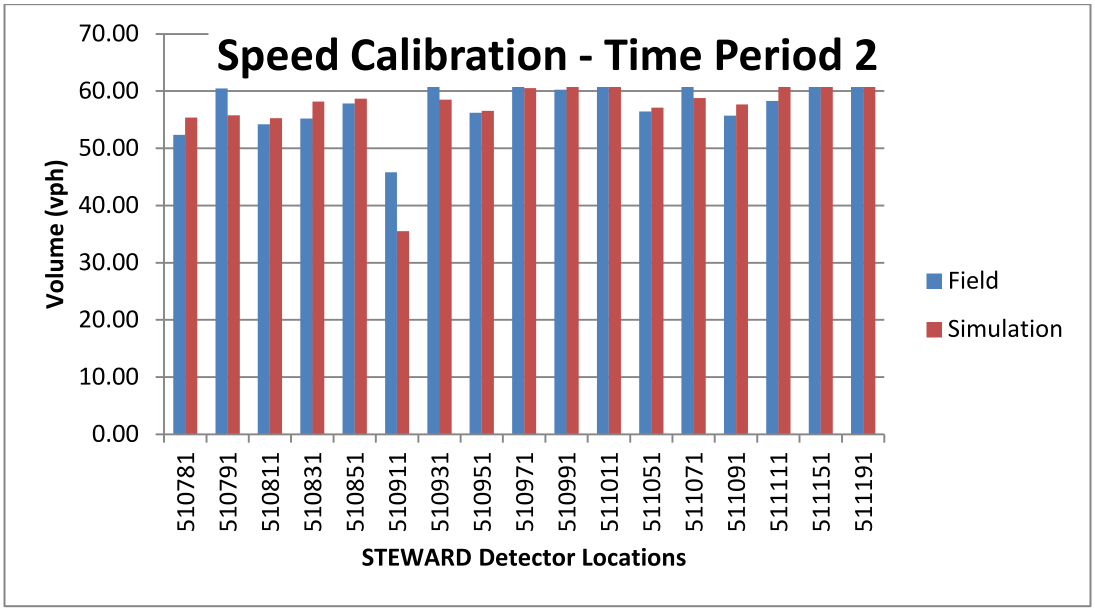

Figure F.4 Comparison between simulation speeds and field speeds for Time Period 2

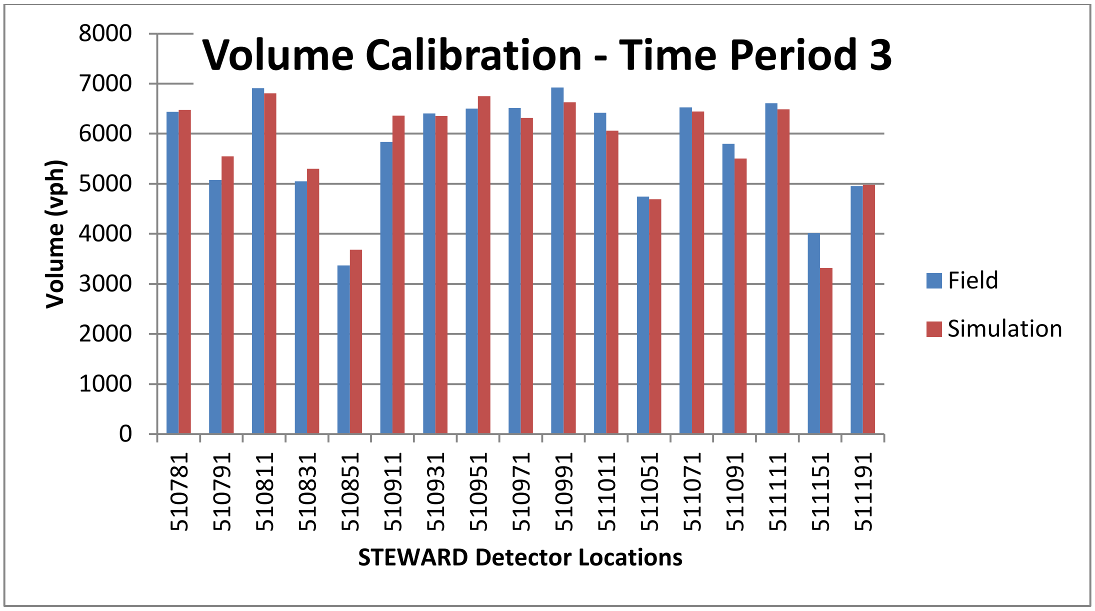

Figure F.5 Comparison between simulation volumes and field volumes for Time Period 3

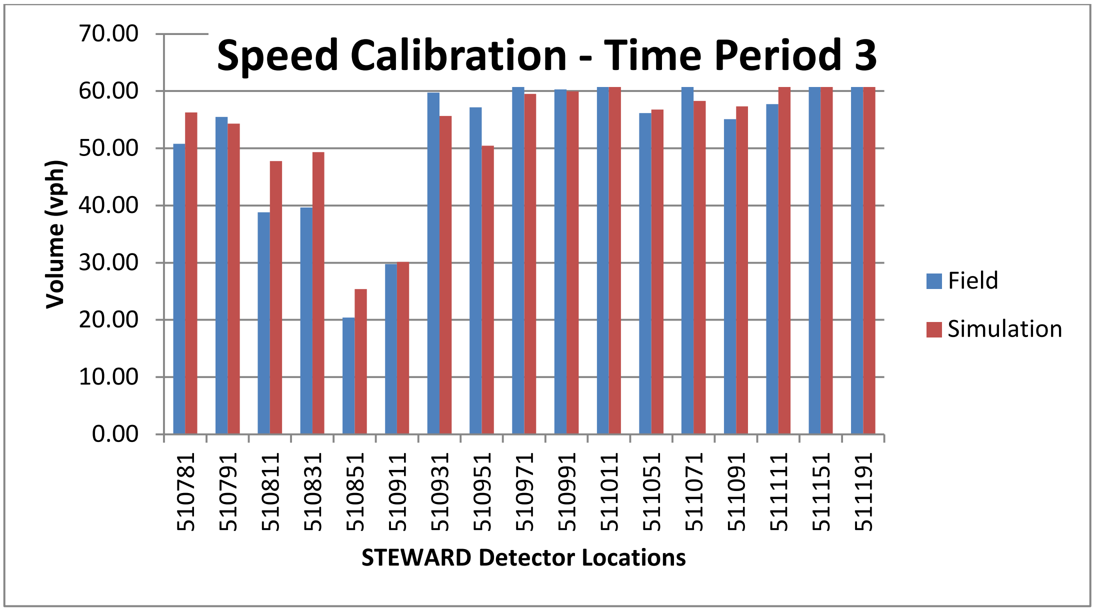

Figure F.6 Comparison between simulation speeds and field speeds for Time Period 3

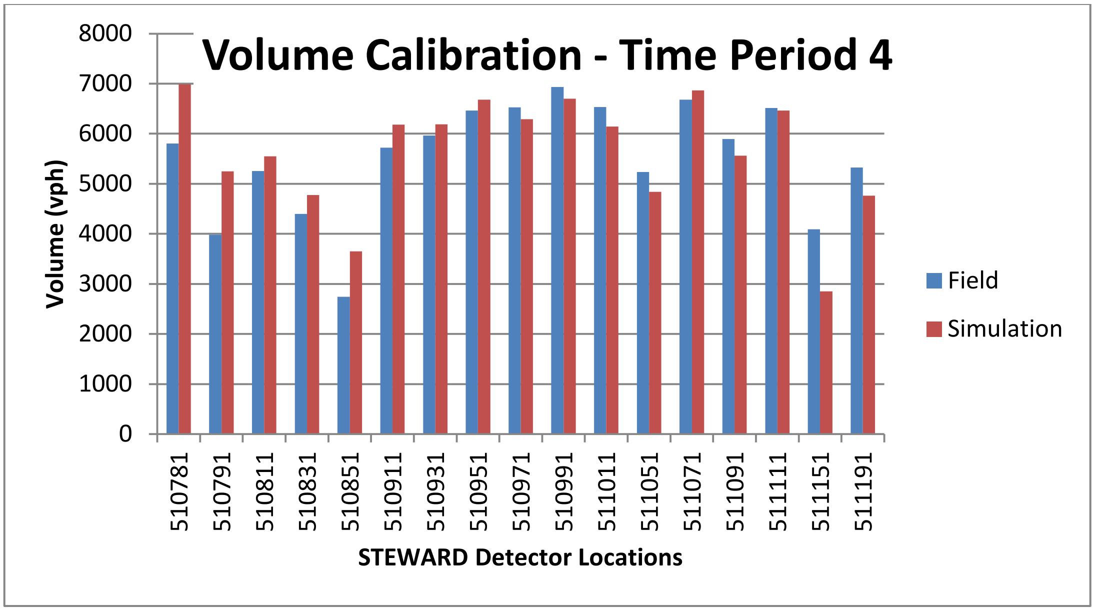

Figure F.7 Comparison between simulation volumes and field volumes for Time Period 4

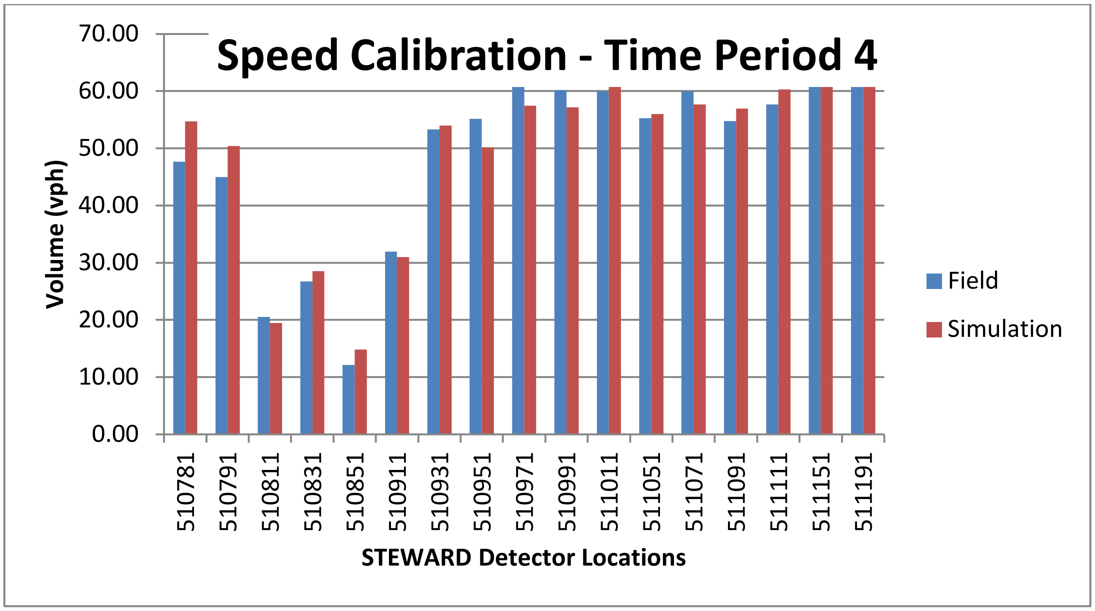

Figure F.8 Comparison between simulation speeds and field speeds for Time Period 4

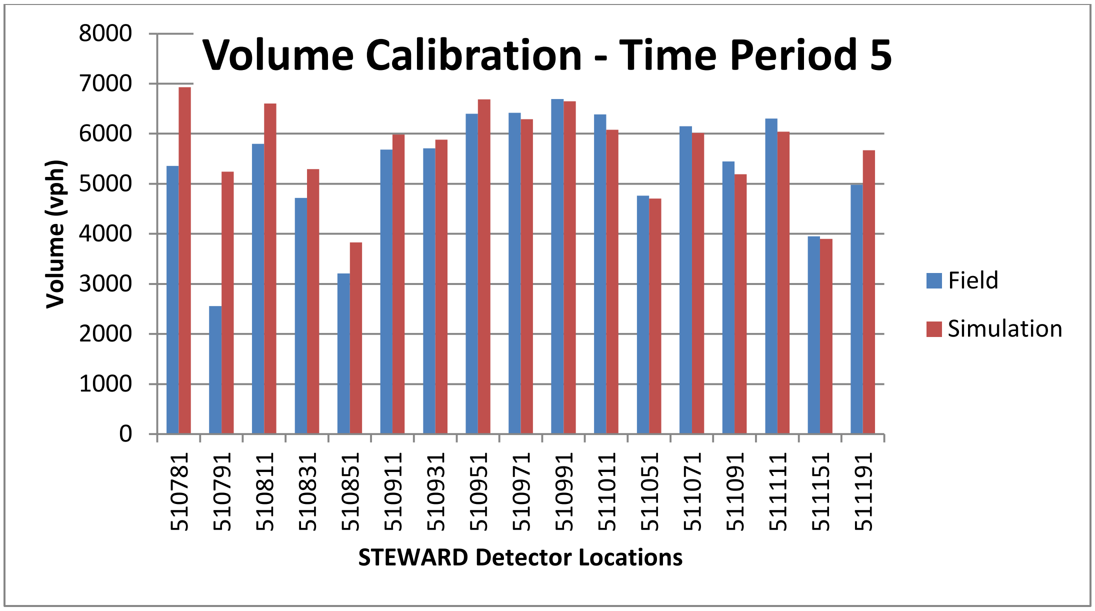

Figure F.9 Comparison between simulation volumes and field volumes for Time Period 5

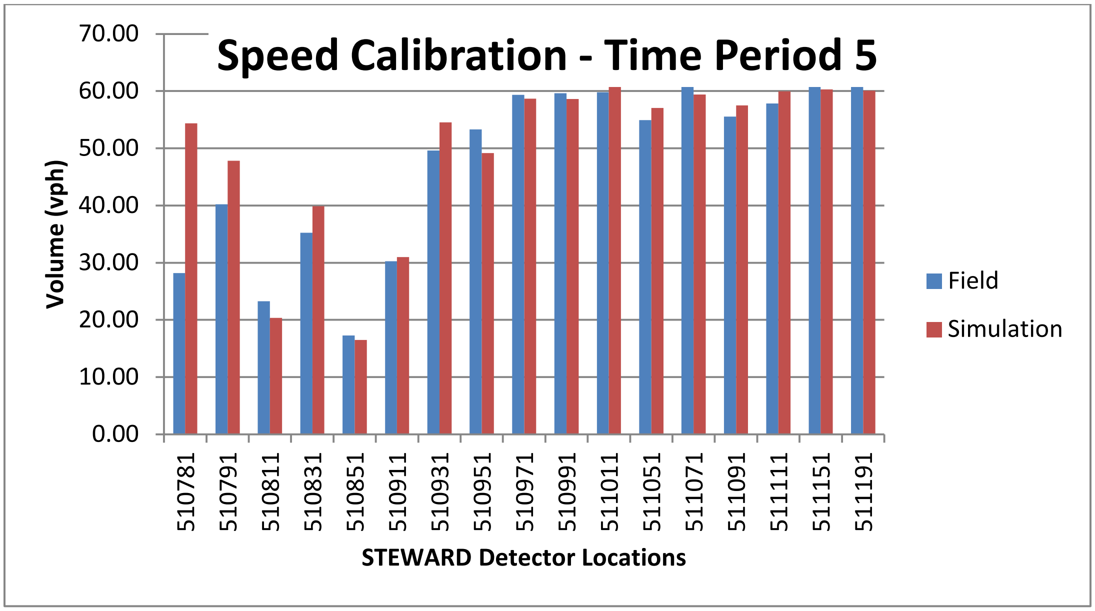

Figure F.10 Comparison between simulation speeds and field speeds for Time Period 5

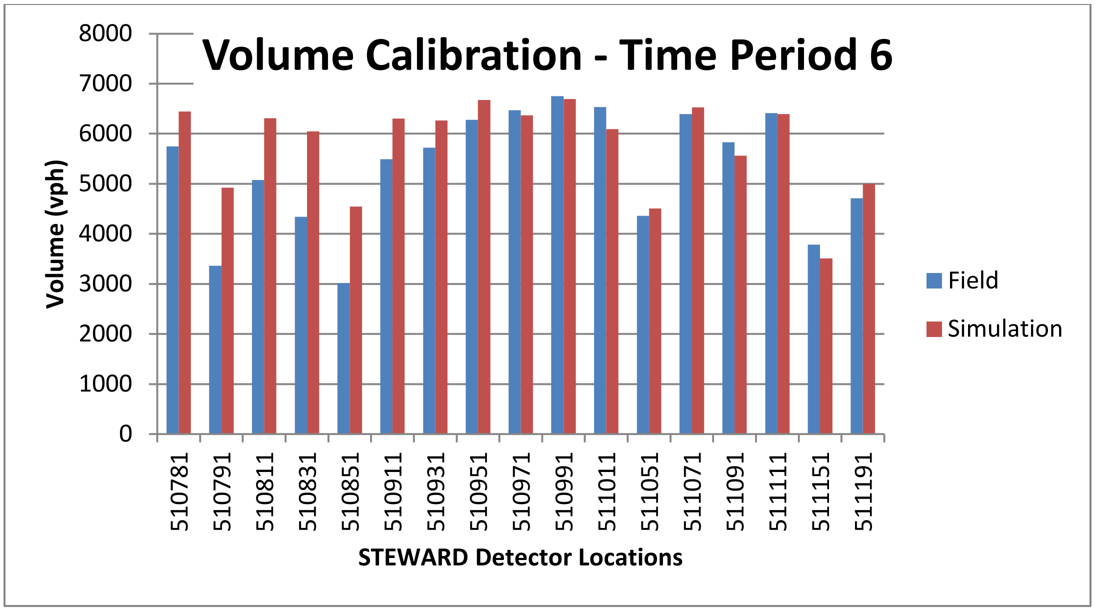

Figure F.11 Comparison between simulation volumes and field volumes for Time Period 6

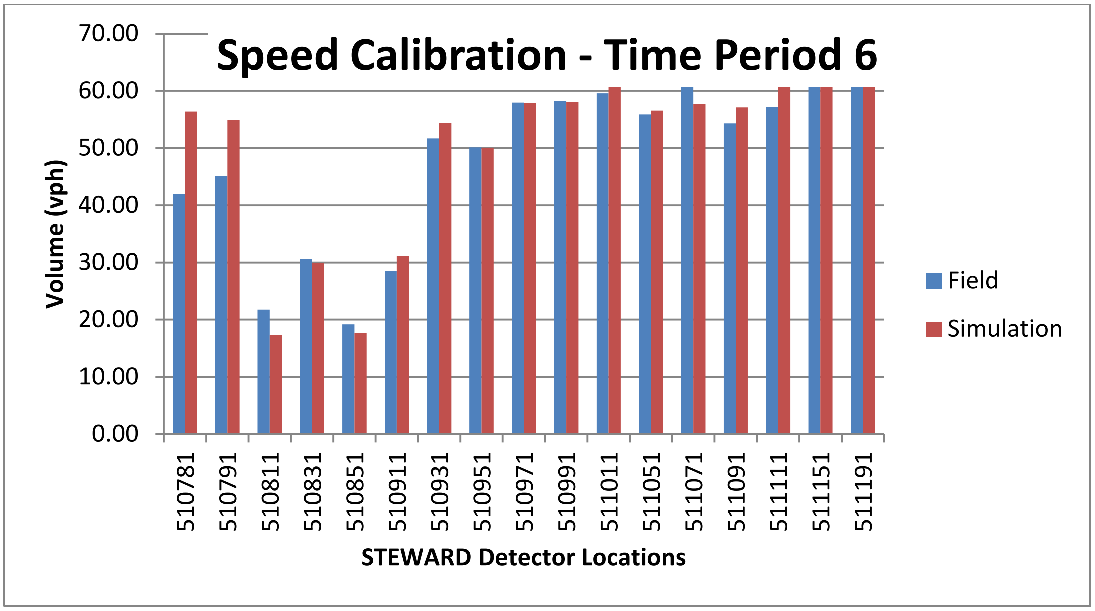

Figure F.12 Comparison between simulation speeds and field speeds for Time Period 6

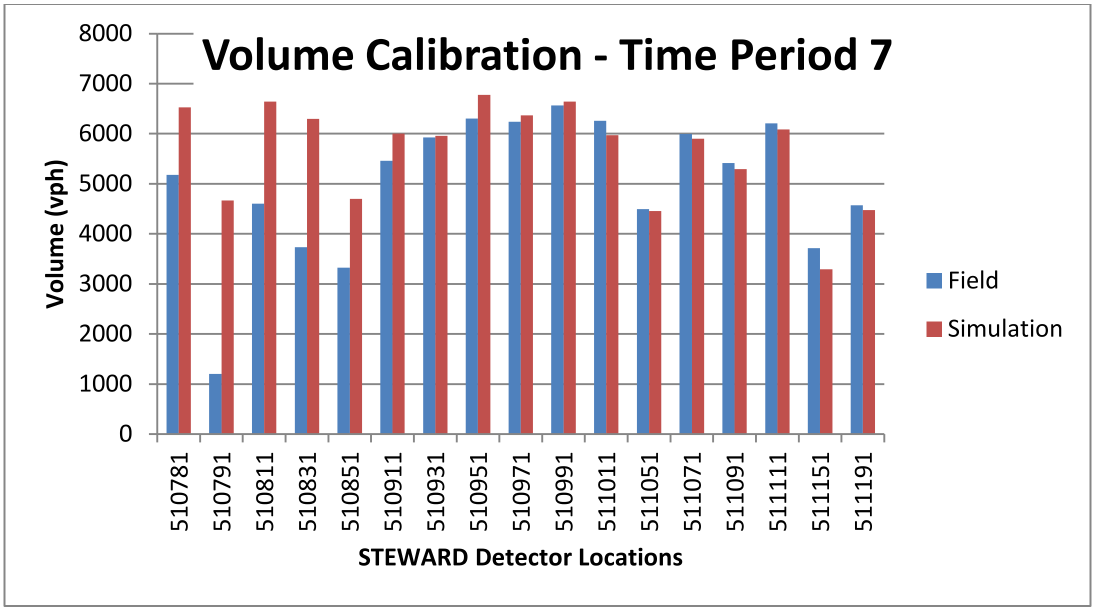

Figure F.13 Comparison between simulation volumes and field volumes for Time Period 7

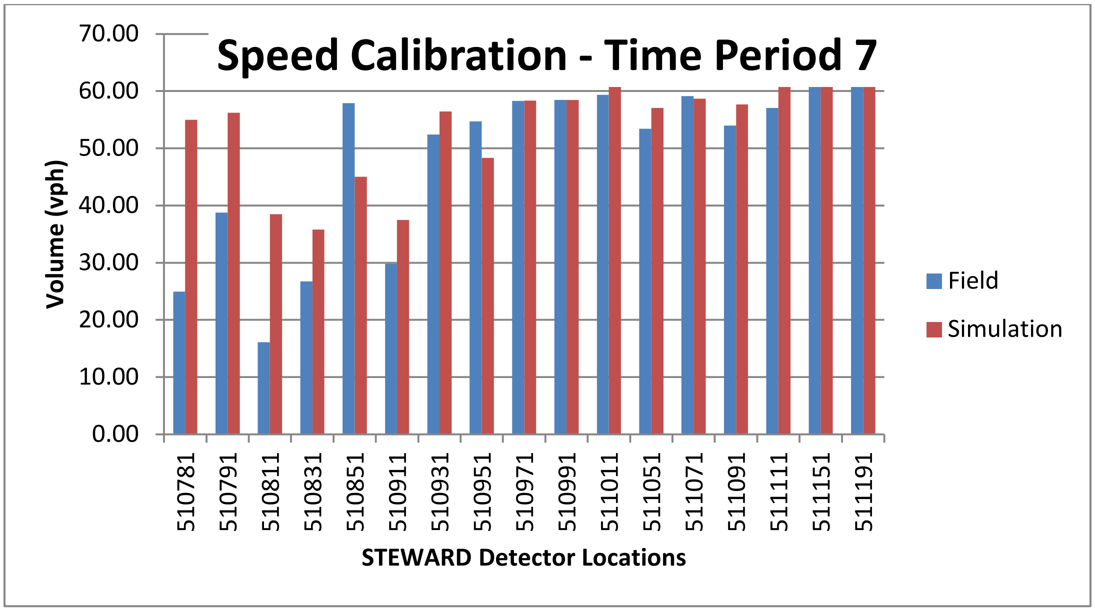

Figure F.14 Comparison between simulation speeds and field speeds for Time Period 7

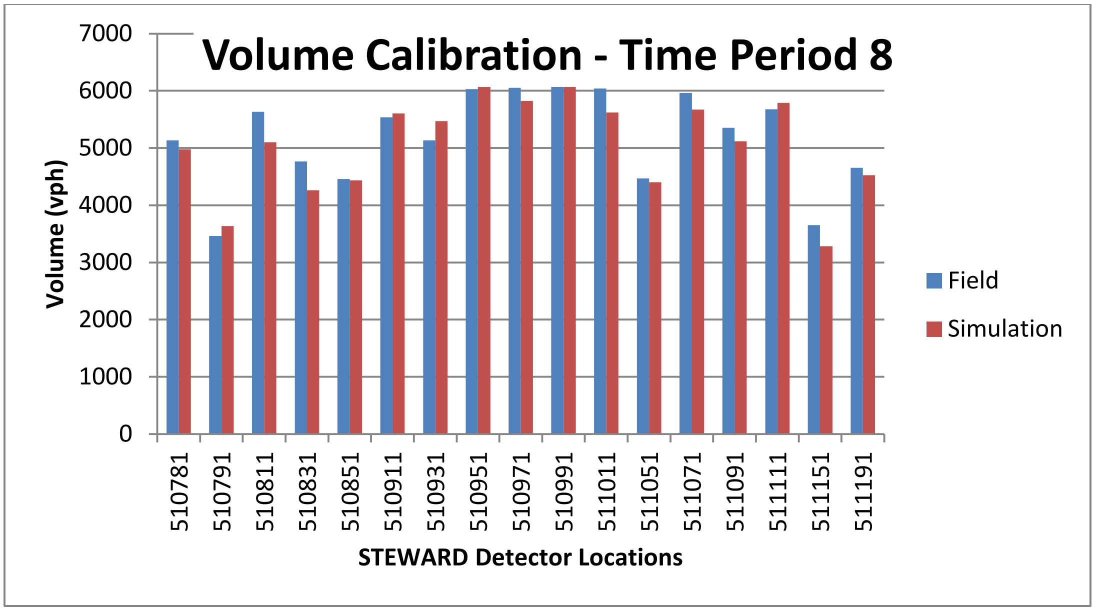

Figure F.15 Comparison between simulation volumes and field volumes for Time Period 8

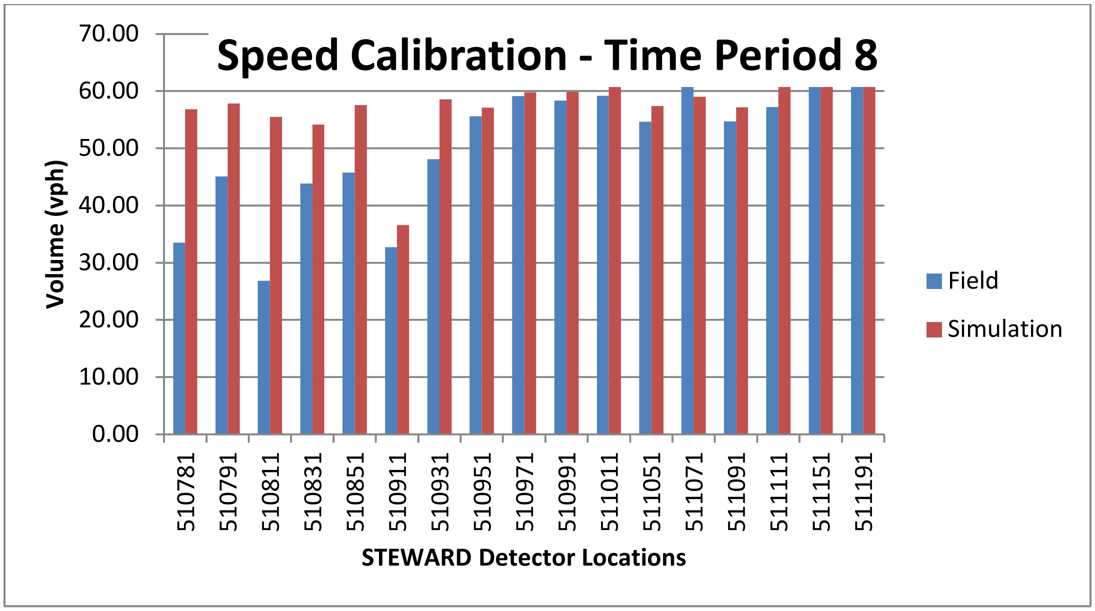

Figure F.16 Comparison between simulation speeds and field speeds for Time Period 8

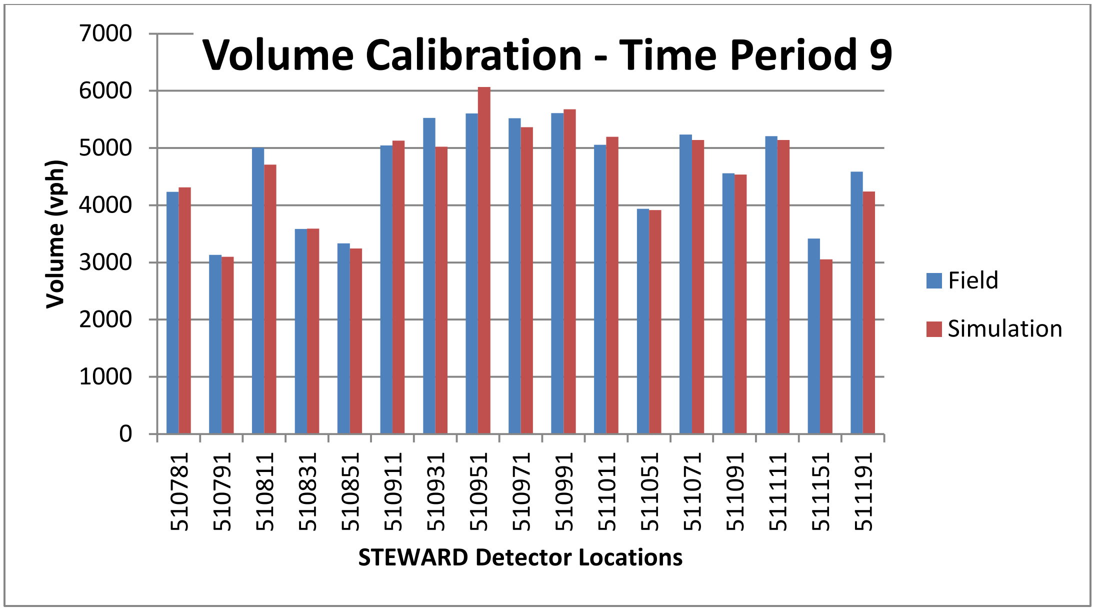

Figure F.17 Comparison between simulation volumes and field volumes for Time Period 9

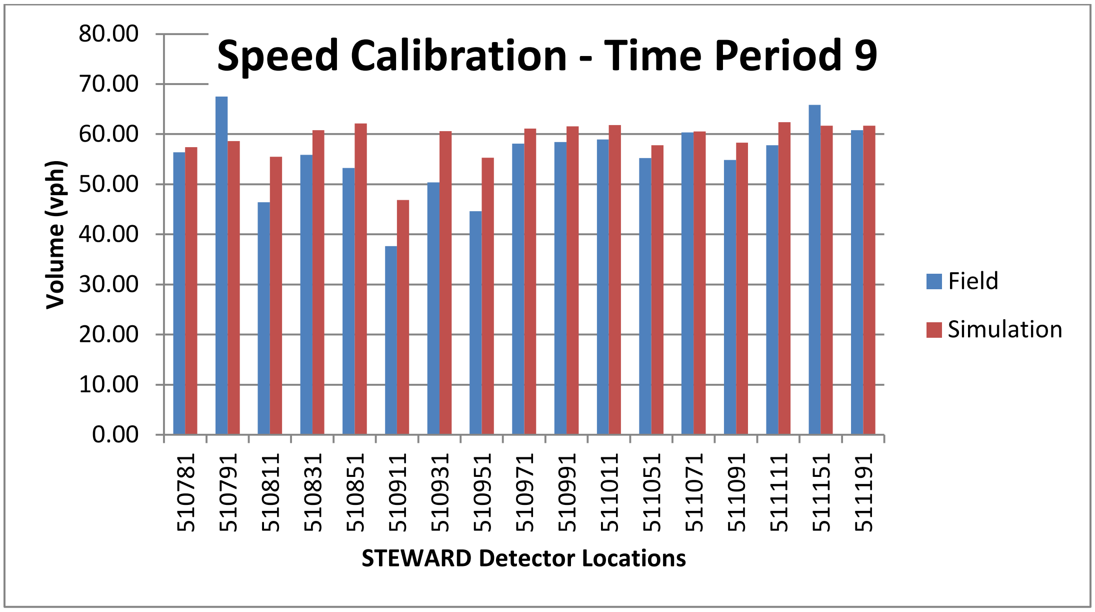

Figure F.18 Comparison between simulation speeds and field speeds for Time Period 9

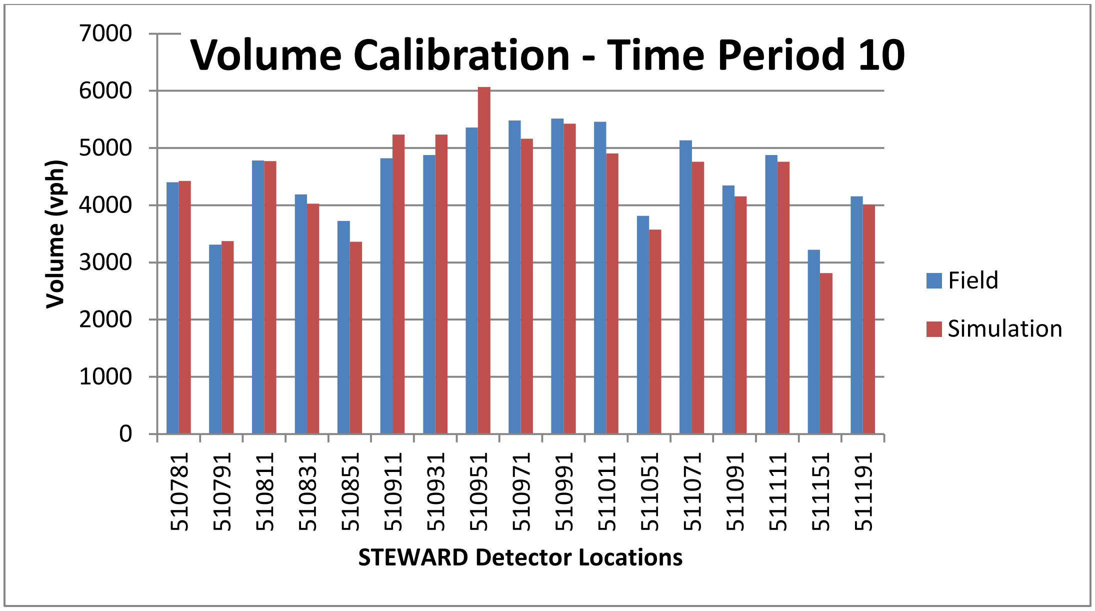

Figure F.19 Comparison between simulation volumes and field volumes for Time Period 10

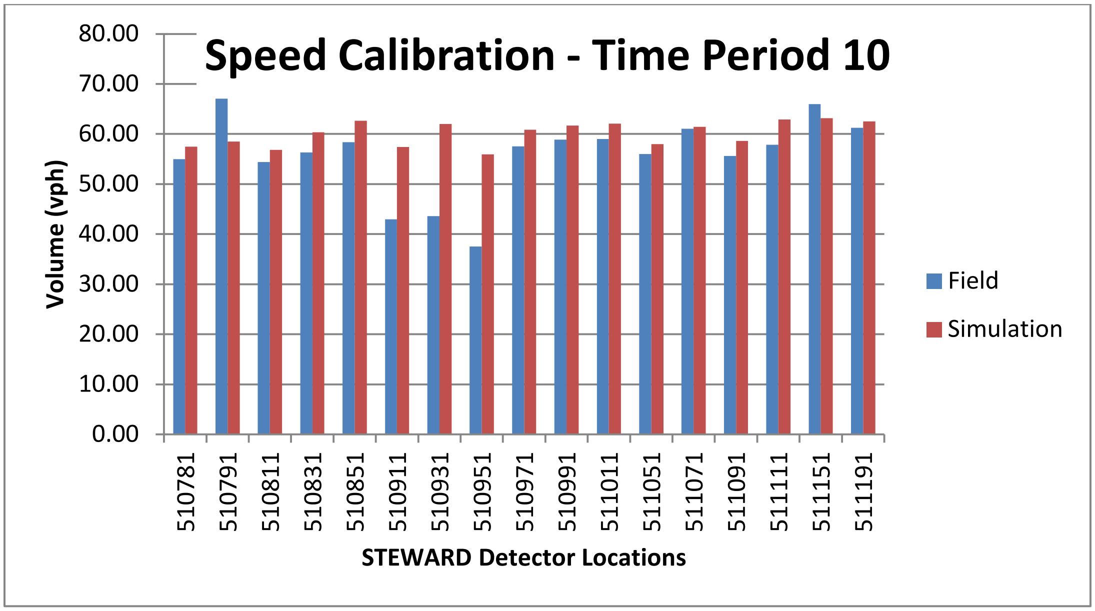

Figure F.20 Comparison between simulation speeds and field speeds for Time Period 10

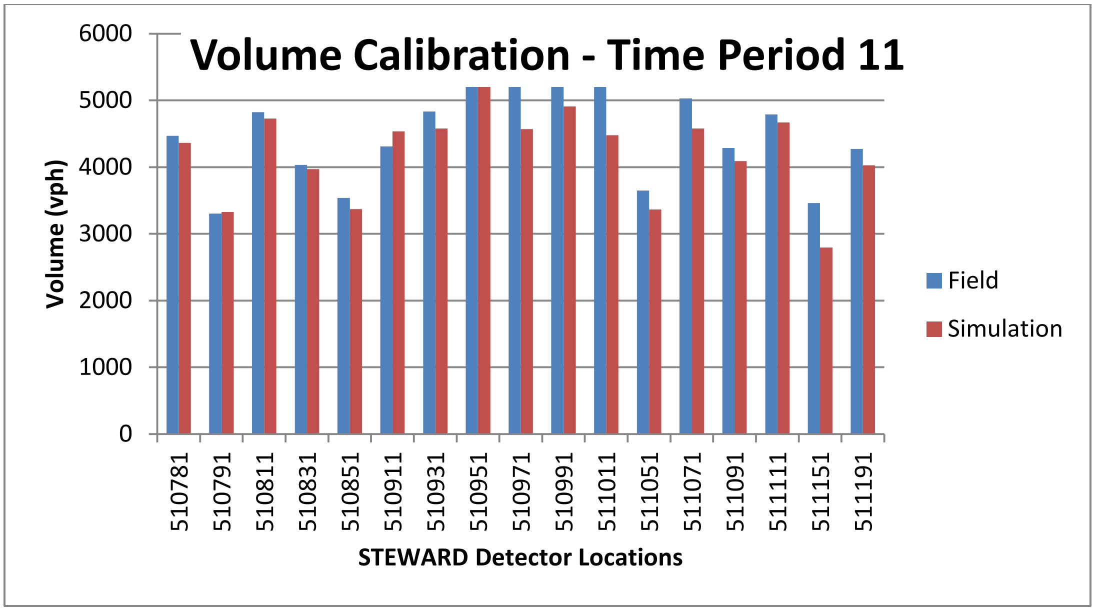

Figure F.21 Comparison between simulation volumes and field volumes for Time Period 11

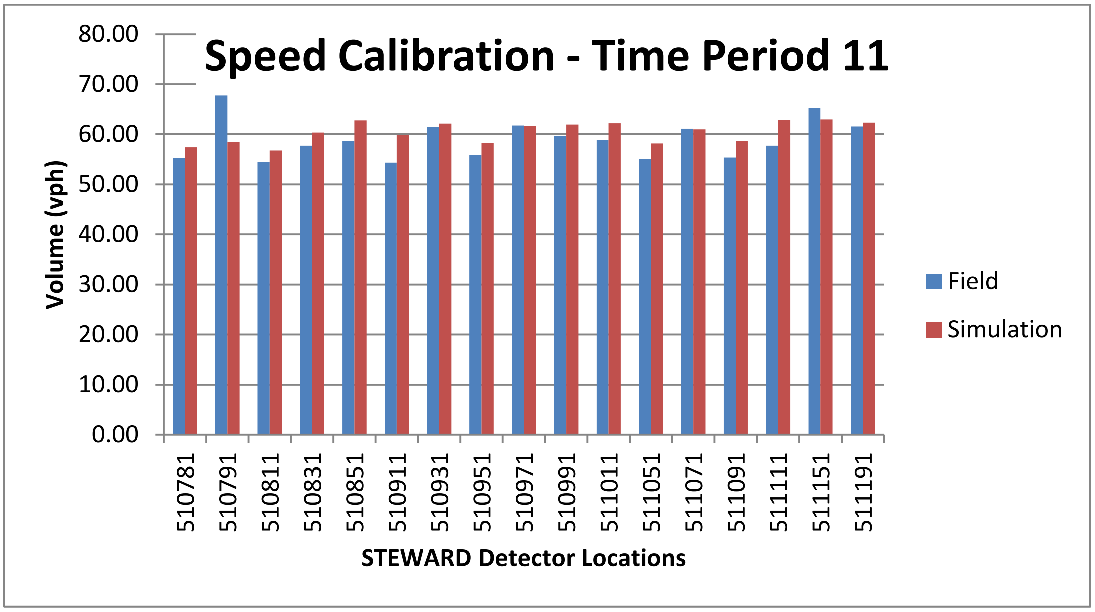

Figure F.22 Comparison between simulation speeds and field speeds for Time Period 11

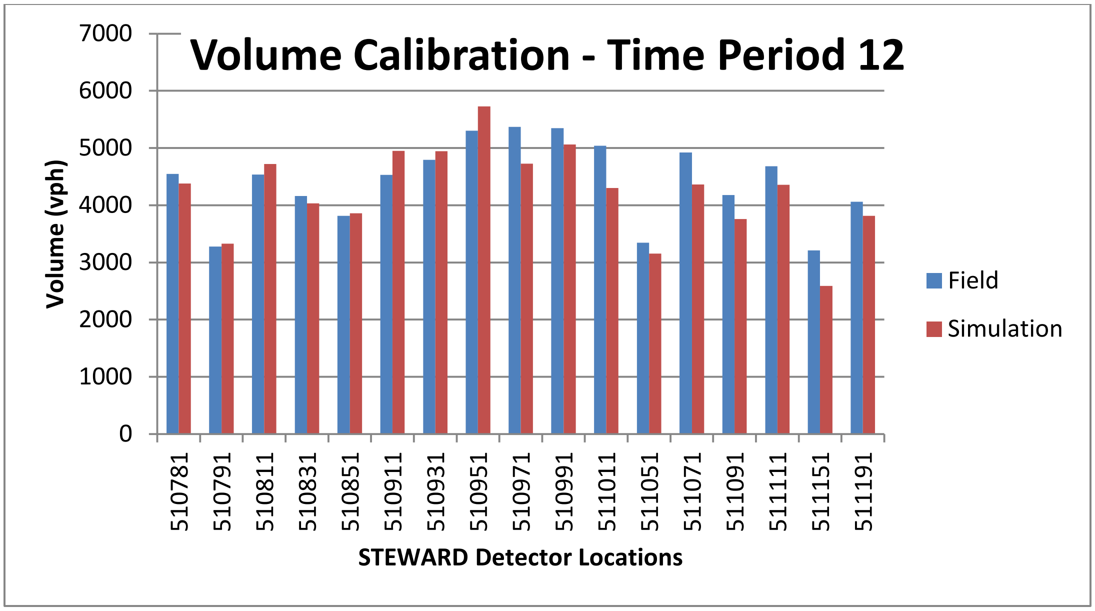

Figure F.23 Comparison between simulation volumes and field volumes for Time Period 12

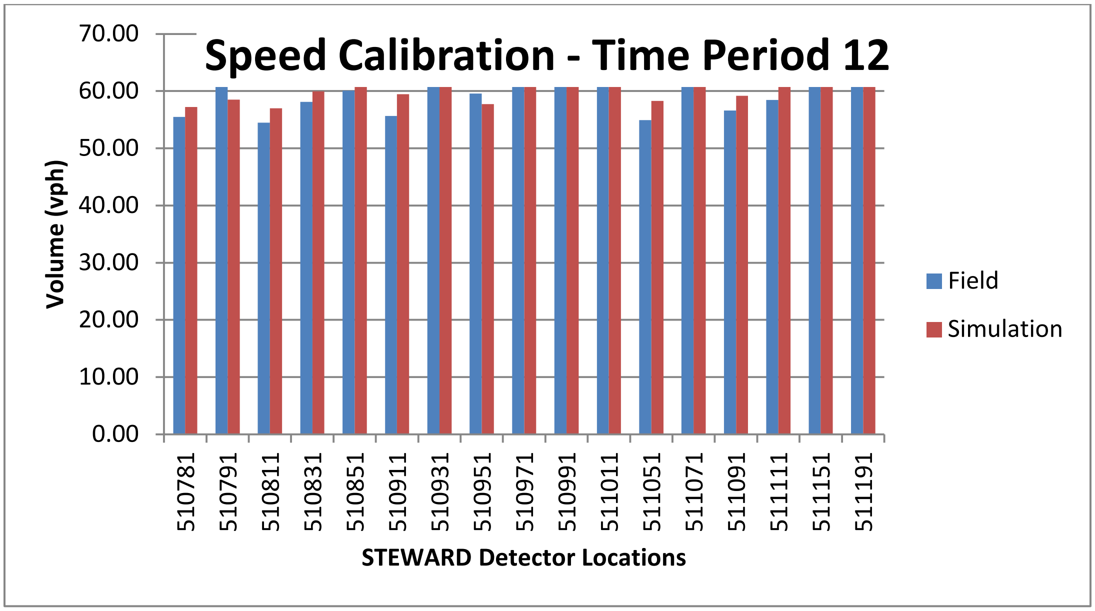

Figure F.24 Comparison between simulation speeds and field speeds for Time Period 12