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NATIONAL CENTER FOR TRANSPORTATION SYSTEMS PRODUCTIVITY AND MANAGEMENT

Performance Measurements of Transportation Systems based on Fine-Grained Data Collected by AVI and AVL Systems

Contract # DTRT12GUTC12 with USDOT Office of the Assistant Secretary for Research and Technology (OST-R)

Final Report

June 2014

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Volume-I-: Applications of Transit Signal Priority Technology for Transit Service

This is Part of FIU-UCF (FIU Lead) Project Titled
"Performance Measurements of Transportation Systems based on Fine-Grained Data Collected by AVI and AVL Systems"

Contract # DTRT12GUTC12 with Research and Innovative Technology Administration (RITA)

Final Report
June 30, 2014

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UCF Portion of the UTC Project: Applications of Transit Signal Priority Technology for Transit Service

Detailed UCF Role in UTC Project Titled
"Performance Measurements of Transportation Systems based on Fine-Grained Data Collected by AVI and AVL Systems"

1. Executive Summary

Transit Signal Priority (TSP) is a system that provides signal priority to TSP-equipped transit vehicles through signalized intersections. To understand the benefits of TSP to the transit rider, it is necessary to evaluate through data analysis and micro-simulation how TSP affects travel time and to determine if TSP causes any other changes in different traffic conditions for both buses and other vehicles. Utilizing TSP can reduce delays, and therefore travel time, for the buses while minimizing impacts on traffic signal operations and other traffic. A reduction in bus delay and travel times will increase the attractiveness of the bus transit compared to other modes of transportation and can reduce the number of single occupant vehicles on the nation's roadways. This can reduce greenhouse gas emissions and help create a sustainable component of the transportation system. This research collected real world bus data and developed micro-simulation models to study the effects of TSP on bus operation and the signalized intersections within the study corridor. The results showed that, under certain scenarios, TSP was effective in reducing bus travel times, reducing overall bus delay, and improving schedule adherence while minimizing the impact to the side street operations. Additionally, the micro-simulation found that the average number of stops in the corridor was reduced for all vehicles, which can reduce the chance of vehicle to vehicle crashes.

Environmental models were also developed to determine the environmental effects of three different real world TSP scenarios: TSP system turned off (No TSP); TSP system turned on unconditionally (Unconditional TSP); and TSP system turned on only under certain conditions of bus behind schedule (Conditional TSP 3 and 5 minutes behind). Information from the micro-simulation models was used to determine average queue lengths and the resulting vehicle emission models. These emission models showed that TSP reduced most emissions for both the Unconditional and Conditional scenarios.

2. Introduction

The University of Central Florida's Department of Civil, Environmental, and Construction Engineering in joint cooperation with the City of Orlando performed research on the LYNX Bus system involving Applications of Transit Signal Priority Technology for Transit Service. This is the final report on the collaborative effort between the University of Central Florida (UCF) and Florida International University (FIU) on the project titled "**Performance Measurements of Transportation Systems based on Fine-Grained Data Collected by AVI and AVL Systems**," Volume-I-, sponsored by the Georgia Institute of Technology University Transportation Center (hence referred to as Georgia Tech UTC). FIU was the lead institution in this competitive funding of this project.

UCF's specific role in this project was to study the applications of transit signal priority (TSP) technology on bus service in Orlando, Florida (US). TSP provides preferential treatment for bus transit vehicles when travelling through signalized intersections equipped with TSP technology. The purpose of this research was to demonstrate the effectiveness of TSP in improving bus travel time along a signalized corridor equipped with TSP in a simulated environment using real world data. Three different TSP activation scenarios were studied and compared to a case without TSP (No TSP). These scenarios are the unconditional activation of TSP for all TSP-equipped buses (Unconditional TSP), the conditional activation of TSP for buses three (3) minutes behind schedule (Conditional TSP 3 minutes behind), and the conditional activation of TSP for buses five (5) minutes behind schedule (Conditional TSP 5 minutes behind). The study showed that both Conditional TSP scenarios significantly improved bus travel times compared to no TSP with minimal effects on delays for crossing street traffic. Unconditional TSP resulted in significant crossing street delays for some of the TSP signalized intersections with only minor additional improvements to bus travel time compared to the Conditional TSP scenarios.

The test corridor containing the signals equipped with TSP was located on International Drive (I-Drive) in Orlando, Florida (US). Bus service along this corridor is operated by LYNX, a local government agency responsible for area transit service. The corridor contains a portion of LYNX bus route 8 (LINK 8) on I-Drive including TSP signalized intersections at Universal Boulevard, Pedestrian Signal at Sheraton, Grand National Drive, Municipal Drive, Del Verde Way, and Fun Spot Way (formerly Touchstone).

Testing TSP in a localized real world setting is necessary to show the system is effective before it can be expanded. In this era of governmental budget constraints, it is imperative to show that a system like TSP will work and can be effective at a test location, like the I-Drive test corridor, before it can be expanded to other transit lines in the Orlando area. Expansion of the TSP system without proper testing and careful evaluation can be a costly and fruitless endeavor. The agencies responsible for future expansion want to ensure that expansion of the TSP system is cost effective and beneficial to their patrons by reducing bus travel time and improving schedule reliability. Also, minimizing cross street delay through simulations is a critical aspect of testing to prove that the system does not have significant negative effects.

There are many types of TSP systems; this project used OPTICOM™ GPS Technology. This system is manufactured by Global Traffic Technologies (GTT) located in St. Paul, Minnesota (US). OPTICOM™ GPS Technology was chosen for this research since the existing ITS infrastructure in the city of Orlando, including the fiber optic network and signal controllers, can be adapted for this type of TSP technology. Additionally, GPS signals are advantageous in urban areas, such as the I-Drive test corridor, since the signals can travel around corners or obstructions. I-Drive has numerous buildings, landscaping and curved roadways near signals, making this technology a smart choice. A discussion of other TSP systems is provided in the literature review section of this research report.

To allow for modeling and statistical analyses, actual bus data was required for this research. This data, including corridor travel time, delay, and passenger counts, was collected by riding buses along the test corridor. Data was collected on multiple days for No TSP, Unconditional TSP, and Conditional TSP to allow for comparison and to identify the effects of TSP in reducing average passenger delay. In addition to analyzing this real world data, traffic modeling was performed using the micro-simulation program VISSIM. This program, developed by the PTV Planung Verkehr AG in Kralsruhe, Germany, allows for the simulation of traffic patterns and provides a variety of data concerning the simulation [**1**]. VISSIM was utilized to determine performance metrics of the corridor, including the average speed profiles for all vehicles, the average travel times for all vehicles, calibration of turning movement counts at all signalized intersections, and arterial performance along the corridor for the different TSP scenarios studied.

The environmental effects of TSP were also researched. To evaluate the life cycle environmental effects of the different TSP strategies, the Argonne National Lab's new Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool was used. AFLEET uses Motor Vehicle Emission Simulator (MOVES) [**2**], an EPA based model, and certification data to determine vehicle emissions (AFLEET, 2013) [**3**].

3. Objectives

The following were the objectives of this research:

- Provide a better understanding of how TSP causes changes in different traffic conditions for both bus and regular vehicles.
- Determine if TSP improves travel time efficiency by reducing travel time and delay for the bus while minimizing the impacts on traffic signal operations.
- Model the overall impact of the TSP system on the local traffic network, including side streets at signalized intersections in the TSP corridor, to check for any possible negative effects.
- Show that TSP can be used to create a more sustainable transportation system by reducing bus delay and travel time, therefore increasing the attractiveness of the bus compared to other modes of transportation (especially single occupant vehicles).

4. Site Selection

In October 2011, the City of Orlando implemented a demonstration project for TSP on I-Drive between Universal Boulevard and Touchstone Drive near Universal Studios (see Figure 1). For this initial implementation, TSP was provided for any Opticom transponder equipped bus serving LINK 8 regardless of schedule adherence or passenger count. Since this approximately 1.1 mile corridor was already established for TSP, it was determined to expand the corridor to run a larger experiment and demonstration. The focus of the new expansion was to test Unconditional and Conditional TSP preemption settings, and to compare these scenarios with the No TSP condition.

The corridor contains seven (7) TSP equipped signals: Universal Boulevard, Kirkman Road, Pedestrian Signal at Sheraton, Grand National Drive, Municipal Drive, Del Verde Way, and Fun Spot Way. However, it was discovered that two of these signals (Kirkman and Fun Spot) had some communication issues; this is shown in Section 10.4. Since Kirkman Road had more than communication issues as it gave preferential treatment to the higher volume Kirkman Road and not to I-Drive, it was not shown as a TSP signal but included in data exploration. The Pedestrian Signal at Sheraton had communication issues and rarely affected traffic operations. It was discounted in data exploration so that only six signals were analyzed.

Figure 1: Site map of I-Drive

The I-Drive corridor is a popular tourist commercial roadway that serves a high vehicular and pedestrian volume. The corridor is serviced by LYNX LINK 8, which serves as far south as the Orlando Premium Outlets on Vineland Road (south of SR 528, Beachline Expressway) and as far north as Lynx Central Station in Downtown Orlando (see Figure 2). It also serves the Orange County Convention Center. The buses along the corridor travel in mixed traffic (but will have dedicated lanes by November 2014).

This research will provide a better understanding of the TSP effects on the traffic through the corridor under different traffic conditions; determine the overall impacts of the TSP system on the local traffic network, including side-street signal delay; and improve bus travel time and reduce delay through the corridor while minimizing the impacts on traffic signal operations.

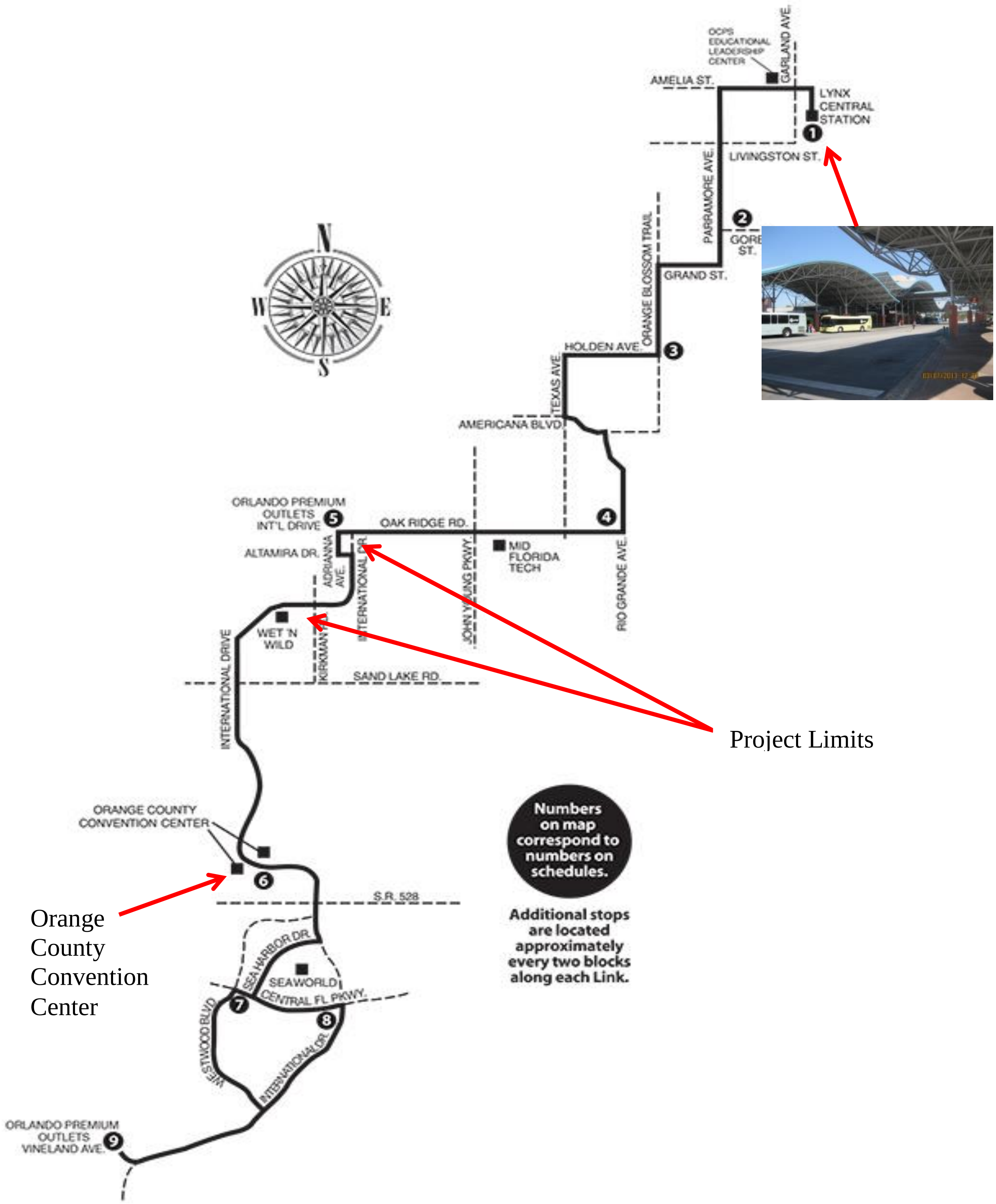

Figure 2: A portion of link 8 route that travels from the Orange County convention center to downtown Orlando at LYNX central station (source: Lynx 2014)

Details of LYNX bus route (LINK 8) along TSP Corridor

Figure 3 shows the I-Drive test corridor, including both the eastbound to northbound movement, or eastbound direction, and the westbound to southbound movement, or westbound direction. It also shows the signalized intersections and identifies which signals are equipped with TSP and which signals are not. The eastbound route starts at bus stop 1, located at the tourist attraction of Wet 'n' Wild, and ends at stop 9, the shopping area of the Orlando Premier Outlets on West Oak Ridge Road, for a total distance of 10,190 feet. The westbound route starts at bus stop 10, the Orlando Premier Outlets, and ends at stop 17, Walgreens Pharmacy just south of the Universal/I-Drive intersection, for a total distance of 10,243 feet.

There is an additional signal location at the Sheraton Hotel; this is a mid-block pedestrian crossing and was not included in the study listing because the traffic signal rarely caused traffic to stop. This signal is TSP equipped, but had very few calls for priority during the Unconditional and Conditional phases. Since this signal had a very minimal effect on traffic, it was not considered in this research.

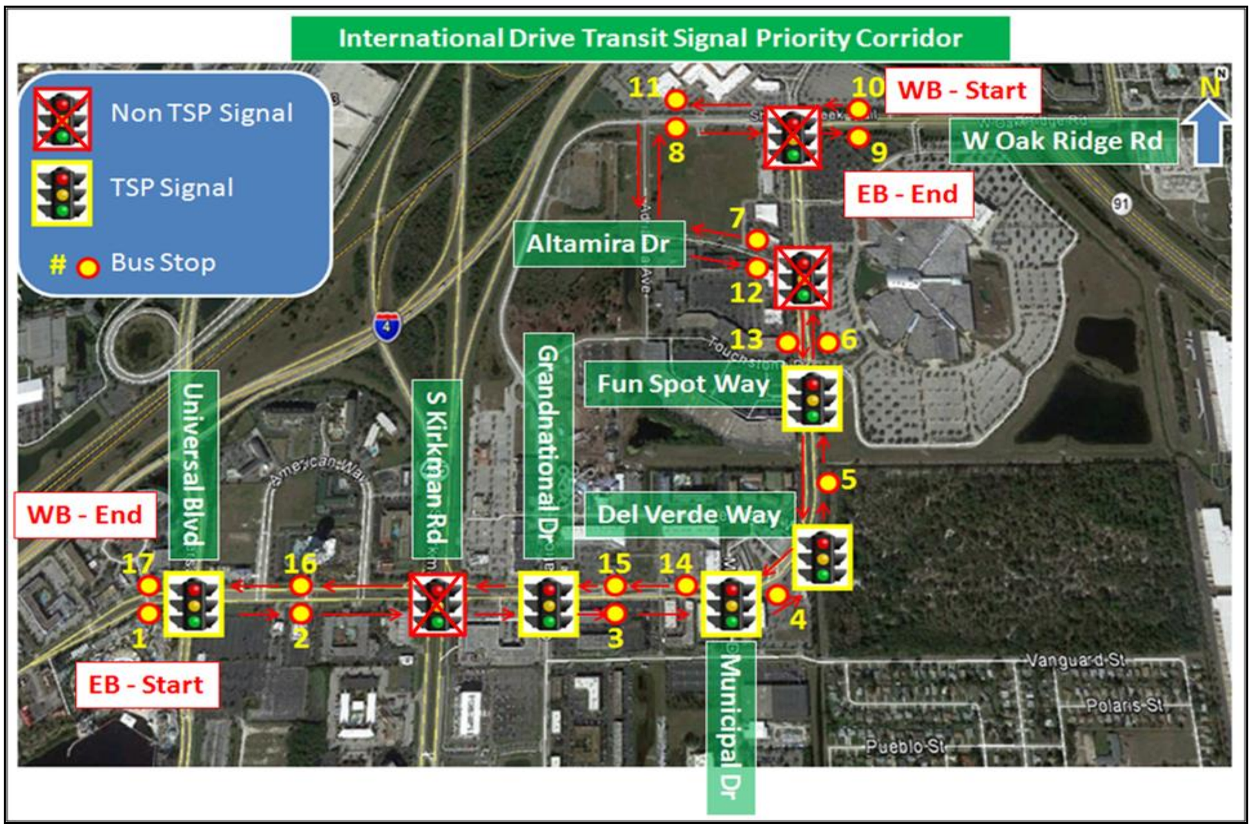

Figure 3: I-Drive TSP corridor

5. Equipment Required

The TSP technology used along the study corridor is the Opticom GPS system manufactured by Global Traffic Technologies (GTT) based in St. Paul, Minnesota. This system was chosen for this field study since the existing City of Orlando ITS infrastructure supports this type of system.

Figure 4 shows the equipment necessary for both the traffic signal controller and the transit buses in order for the TSP to function. The figure shows the GPS Antenna, Opticom Phase Selector in the signal cabinet, controller in the signal cabinet with TSP settings, and the IR/GPS Emitter of the bus.

The Opticom GPS antenna is mounted on the mast arm or concrete strain pole at the signal intersection. The antenna is then connected by cable to the controller cabinet electronics. The controller cabinet includes the Opticom GPS phase selector, the controller unit with the TSP settings, and Ethernet communication equipment. The latter allows communication between the signal and the City of Orlando's Traffic Management Center (TMC) located at the Orlando Executive Airport near State Road 408 east of downtown Orlando.

The bus contains the Opticom GPS emitter. This emitter unit is connected to the AVL system in the bus by hard wiring a cable that allows for the bus location to be sent to the LYNX central office. The AVL location determines if the bus is behind schedule by three minutes or more. If this occurs, the Opticom GPS emitter is activated, sending a signal to the antenna at the TSP equipped intersection. The components in the controller cabinet then activate the TSP and either extend the green signal or truncate the red signal. This TSP call is recorded at the City of Orlando's TMC and is included in the preemption logs; these preemption logs are discussed in Sections 10.3 and 10.4.

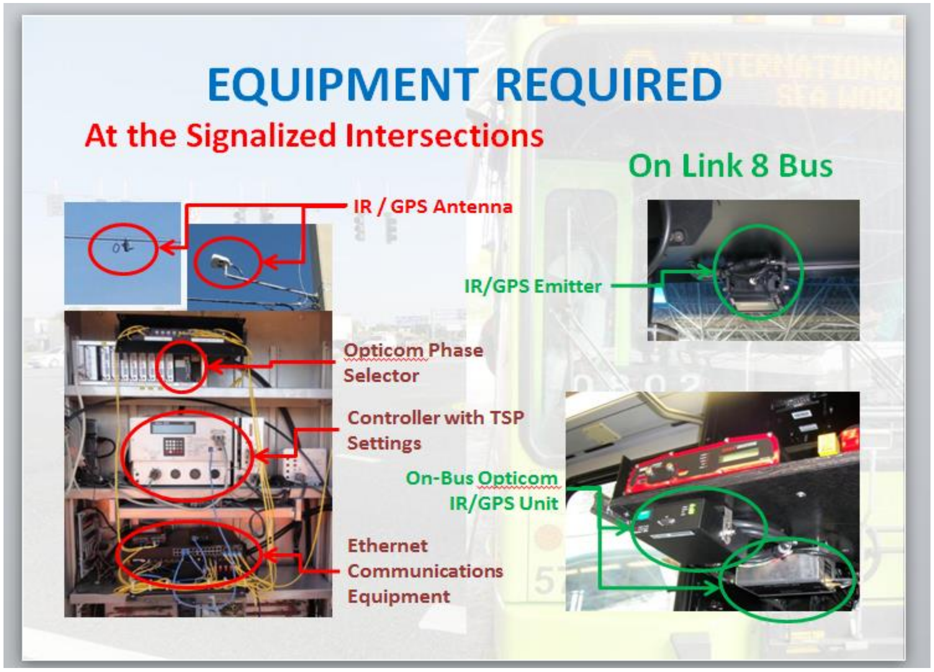

Figure 4: TSP equipment required (source: Kittleson and Associates 2013)

Figure 5 is an example of the Opticom GPS antenna at the TSP signal at Del Verde Way along the I-Drive corridor. This location is near the curve on I-Drive that changes the I-Drive travel direction from eastbound to northbound.

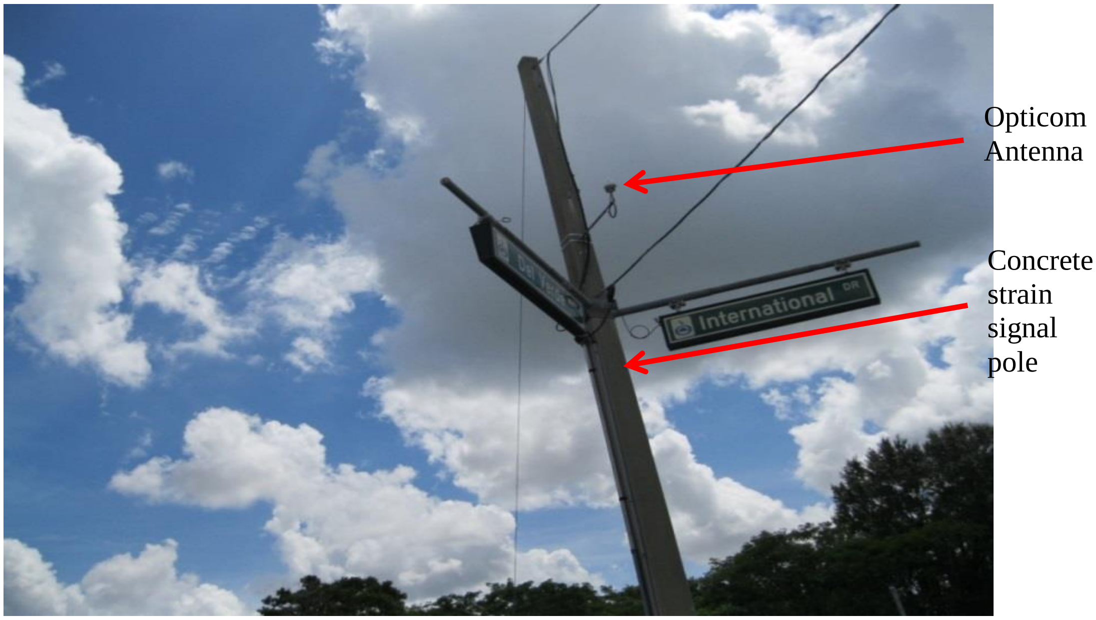

Figure 5: TSP antenna (Opticom GPS) at Del Verde Way and I-Drive

6. Literature Review

A literature review was performed to determine what methods and procedures have been used on previous projects concerning TSP, including any micro-simulation and bus data collection. Research on MOVES was also performed, since MOVES was used to estimate vehicle emissions for the different TSP scenarios. There has been extensive research performed on TSP both nationally and internationally. Many of the studies used VISSIM modeling to optimize the signal coordination with TSP. Other research was devoted to resolve the issue of a system-wide traffic signal operation disrupted by the individual signal use of TSP. The disruption of signal coordination by TSP is a major concern of traffic operation engineers.

Some studies evaluated transit service performance before and after the TSP was deployed. Data in these studies were reviewed and analyzed to evaluate the performance and benefit of the TSP system. In one of these studies, the bus schedule was found to be reduced by two minutes after TSP deployment was used to take full advantage of the conditional priority strategy.

One study discussed how TSP can help make transit service more reliable, faster, and more cost effective. Smith et al., 2005 [**4**] noted that TSP has little impact on general traffic and is fairly inexpensive.

Another study evaluated the conditional TSP condition, which is one type of traffic signal preemption that can produce a reduction in travel time delay for late transit buses. They found that conditional TSP tends to be most effective at lower volume intersections where queuing is less of a problem (Albright and Figliozzi, 2012) [**5**].

Another TSP study discussed the implementation of TSP at more than 240 intersections on seven transit routes in Portland, Oregon (US) in the 1990's. This resulted in TSP equipped buses that would request a priority based on the status of their schedule (behind or not behind schedule). The buses used the 3M Opticom system and an automatic vehicle locator (AVL) system. (Koonce, 2012)[**6**]. No simulation was performed in evaluating the system, but this TSP system is important as it uses a similar type of GPS system as the city of Orlando and is coupled with the AVL as is the system on the LINK 8.

A paper presented at the 2011 ITS World Congress discussed a new TSP concept called "Virtual Loops for Traffic Signal Priority". This involves the use of virtual loops based on the onboard bus computer as a foundation for priority requests at traffic signals in Trondheim, Norway. All data communication for bus positioning is processed through GPRS connection to a central system. After processing the received information, the requests for signal priority are routed to the individual signalized intersections using adaptive signaling (Tveit, 2011) [**7**].

Research also focused on resolving the issue of system-wide traffic signal operations being disrupted by the individual traffic signal called for TSP. The researchers developed real time traffic signal control integrating traffic signal optimization and TSP using Genetic Algorithms (GA). This control included the use of an Artificial Neural Network (ANN) modeling algorithms to resolve this issue. The analysis showed some promising results that the proposed signal control system was able to reduce the overall traffic delay and number of stops. This method improved transit schedule adherence (Ghanim and Abu-Lebdeh, 2012) [**8**].

An analysis of various TSP strategies to improve the performance of a light rail transit corridor used VISSIM to simulate the different TSP strategies at a major intersection during peak hours. Peak hour field data were collected at four intersections along the corridor for use in the calibration of the VISSIM model (Islam et al., 2012) [**9**].

A presentation of different TSP strategies for a future Bus Rapid Transit (BRT) corridor in West Valley City, Utah (US) was studied. The goal was to find the optimal TSP strategy for estimated and planned traffic and transit operations. The study used VISSIM in combination with ASC/3 Software-in-the-Loop simulation. Four different TSP strategies were analyzed; the results showed that TSP with phase rotation and custom TSP should both be considered for implementation. Custom TSP had more benefits for the bus traffic, However, it had more impact on the other vehicular traffic than TSP with phase rotation (Zlatkovic et al., 2012) [**10**].

A before and after study on TSP was implemented at 27 signalized intersections along Central Avenue in Minneapolis, Minnesota (US). This study showed that TSP deployment effectively reduced the bus travel time by about 4-6% (Liao, 2012) [**11**].

An empirical method discussed what effects to measure both before and after TSP for the I-95 Express Bus Service in South Florida (US). The method involved synchronizing travel time data from the in bus automated passenger counters (APC's) with travel time delay data collected manually by observers riding the bus. The manually collected data included dwell time, turn out delay, signal delay and right turn delay. The results showed a 4% reduction in signal delay and an average travel time savings of nearly 4 minutes in the AM peak with TSP. As a result of these improvements, the operating agency, Broward County Transit in South Florida (US) was able to consider this project a success (Pessaro and Van Nostrand, 2012) [**12**].

A study was performed in Orlando, Florida (US) by Kittleson and Associates that did a before and after evaluation of TSP along I-Drive (this is the same location that was evaluated in this research report). The Kittleson study collected data on traffic volumes, travel times, and passenger counts for two different times of day in both directions with similar active conventions in the area. The results showed that there was a decrease in bus travel time ranging from 2% to 12% with the conditional TSP (three minutes behind schedule) implemented, and an increase in travel time southbound/westbound during the evening period. The latter travel time increase may have been caused by a large increase in passenger load and an increase of vehicle volumes in the PM peak as reported in their study (Kittleson and Associates, Freeman, 2013)[**13**].

Another group performed a before and after study on TSP in Portland, Oregon (US). They found an overall decrease in bus travel time, with major savings occurring during peak travel hours (Kimpel, et al, 2005) [**14**].

North Dakota State University evaluated TSP at three intersections near their college campus in Fargo, North Dakota (US). They found that TSP increased efficiency at two of the intersections in peak hours, and increased efficiency at the other intersection at all times (NDSU, 2009) [**15**].

A report published by the Mineta Transportation Institute on the modeling, calibration and validation of a VISSIM traffic flow simulation in Southern California (US) showed a developed model network requiring large amounts of data including roadway geometry, traffic signal timing, signal coordination, and turning movement volumes. The turning movement volumes at signalized intersections were utilized in the validation of the modeling with the Geoffrey E. Havers (GEH) statistic. The GEH statistic is a formula used by traffic engineers to compare two sets of traffic volumes. Once the network was validated, it allowed different scenarios to be evaluated and modeled on different emergency plans for downtown San Jose's traffic circulation (Pande, Edwards and Yu, 2012)[**16**].

Research was performed in Italy on roundabout design using the results from micro-simulation programs. This research required knowledge of the sample size and necessary input parameters for the model. It discussed the calibration process and compared the model's parameters to real world data. The approach used allowed the model to represent the real-world traffic. The researcher's goal was to minimize any discrepancies between the micro-simulation models and observed field data (Vaiana, and Gallelli, 2011) [**17**].

The calibration and validation of a micro-simulation model was described in research in Niagara Falls, Ontario, Canada for a large urban network. This model was used to assess traffic operations and traffic management which included the deployment of Intelligent Transportation Systems (ITS) in the tourist areas of Niagara Falls. The roadway network included freeways, arterials, and collector roads with a total of ninety signalized intersections. This calibration focused on PM peak hours with comparisons between modeled and observed traffic volumes (Oketch, and Dilwaria, 2011) [**18**].

A 2005 TRB paper discussed the calibration and validation for a network analysis of another area in Niagara Falls, Ontario using the micro-simulation model Paramics. The calibration included comparing the micro-simulation model to the collected field data for traffic volumes, and turning movement counts at intersections. This research also compared average travel times and approach queues (Oketch, and Carrick, 2005) [**19**].

There have been numerous studies that have deployed MOVES as an emissions modeling framework. Beardsley, et al. (2009), [**20**], published a document describing how MOVES works and how MOVES differs from MOBILE6 in terms of capabilities, inputs, and preliminary results Younglove, et al. (2005), [**21**] used this software as a framework to predict emissions across various scales. In this study, various issues associated with on-road emission measurements and modeling was presented. They also examined an example of an on-road emissions dataset and the reduction in estimation error through the addition of a short aggressive driving test to the in-use data.

Cadle, et al. (2005), [**22**] mentioned that there are several modal emissions models. They stated that the most significant efforts in emission modeling have been used in MOVES. Huai, et al. (2005), [**23**] incorporated NH_3 data into a VSP/modal modeling framework. Two modeling approaches were used in their study. One approach used second-by-second NH_3 emissions data to calculate NH_3 emission rates using a VSP binning methodology, as proposed for EPA's MOVES model. The NH_3 emissions module was applied to estimate the current NH_3 emission inventory in the South Coast air basin (SoCAB) and demonstrate the trend of NH_3 emissions inventories from the future mobile source fleet. Wang, et al. (2008), [**24**] used MOVES to estimate energy consumption for vehicles.

The UCF research team found that little research was performed on bus passenger savings and signal by signal travel time savings. To determine these parameters, the UCF team decided to collect the necessary data by riding the bus to determine travel times, stop delays and any bus delays. Collecting this real world TSP data is important to evaluate if the TSP system is effective and should be considered for expansion. Data collection also revealed discrepancies between the real world and simulations. The UCF research team encountered delays in real world scenarios involving passenger boarding and alighting that are difficult to simulate. This experience allowed the research team to understand factors not in human control, including delays caused by weather. Passenger travel times can be simulated, but real world data allowed the research team to better understand reasons why the simulation output is difficult to explain and differs from the real world. Actually riding the bus gave the UCF research team a comprehensive understanding of all the dynamics that affect bus travel times and passenger delay.

7. Methodology

Several aspects of data collection were necessary to provide for a before and after comparison of TSP for the different activation scenarios (No TSP, Unconditional TSP, Conditional TSP). Data on bus delay, travel times, and passenger counts were collected for No TSP, Unconditional TSP, and Conditional TSP 3 minutes behind.

The no TSP case (the before)

For approximately one month from March 6 to April 10, 2013, the existing TSP was turned off at the signal controller for real world data collection to occur with the base signal timing. This required a field technician to physically turn off TSP at each controller cabinet since the installed system could not be shut off remotely.

The unconditional TSP case

Starting in May 2013, the existing TSP was made operational (by enabling the TSP at the signal controller) and data collection occurred with every TSP equipped bus, regardless of schedule, receiving unconditional priority treatment at the TSP equipped signalized intersections.

The conditional TSP case (the after)

Once conditional priority was established, a final set of data was collected from June 3 to September 10, 2013 for comparison against the above cases. This involved the operational bus TSP emitter connected to the AVL system on the 16 equipped LINK 8 buses. The system was programmed to activate the TSP emitter only if the bus was 3 minutes or more behind schedule.

Another source of data was passenger count information provided by the maintaining agency, LYNX. This data was reviewed to determine peak passenger volumes and peak hours. Passenger count data was obtained for three bus links in the I-Drive Corridor between the signalized intersections of Fun Spot Way (Touchstone Boulevard) and Universal Boulevard. The three bus Links were 8, 37 and 42. Analysis of this passenger count data concentrated on LINK 8, since this Link contained the 16 GPS Opticom equipped buses.

The data collected was analyzed to determine the best way to verify if the TSP was effective in this corridor. It was determined to use signal delay and stop delay as measures of the effectiveness of TSP. The signal delays at each intersection were analyzed by comparing the before data (no TSP) to the after data (conditional priority). The delay times at each bus stop were also analyzed; however, there were many variables out of the research team's control that affected this delay. For instance, stop delays can occur for such simple reasons as a patron looking for change, or a patron asking for directions or an unusually heavy passenger load at a particular stop. Statistical analyses were performed on both the signal delay and the passenger delay; these are discussed in Chapter 10.

Several scenarios using VISSIM modeling were developed utilizing the data collected to evaluate the effects of changing the Conditional TSP time behind schedule from 3 minutes to 5 minutes. Other models were developed to determine the average speed profile, the average travel times, turning movement counts at all signalized intersections, and arterial performance along the corridor.

8. System Architecture

The engineering firm Kittelson and Associates in Orlando, Florida (US) designed and implemented the TSP system architecture (Figure 6) and ran test runs to validate the system (Freeman, 2013) [**13**]. The firm designed the system under a design consultant contract to the City of Orlando.

The basic system architecture is composed of two major sub-systems based on the United States (US) National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) 1211 terminology. These sub-systems are a LYNX Conditional Priority Request Generator (PRG) and a City of Orlando Priority Request Server (PRS). However, given limitations in the current components of the system architecture, a transitional hybrid system was needed. This transitional system used the existing distributed architecture with an unconditional PRG on the bus and a PRS in the traffic signal which receives the priority request. The transitional system provided a conditional function through an upgrade to the Automatic Vehicle Location (AVL) system and the LYNX (Transit) Fleet Management Center (FMC) connection to the City's TMC. This provided the first link in developing a PRS at the TMC.

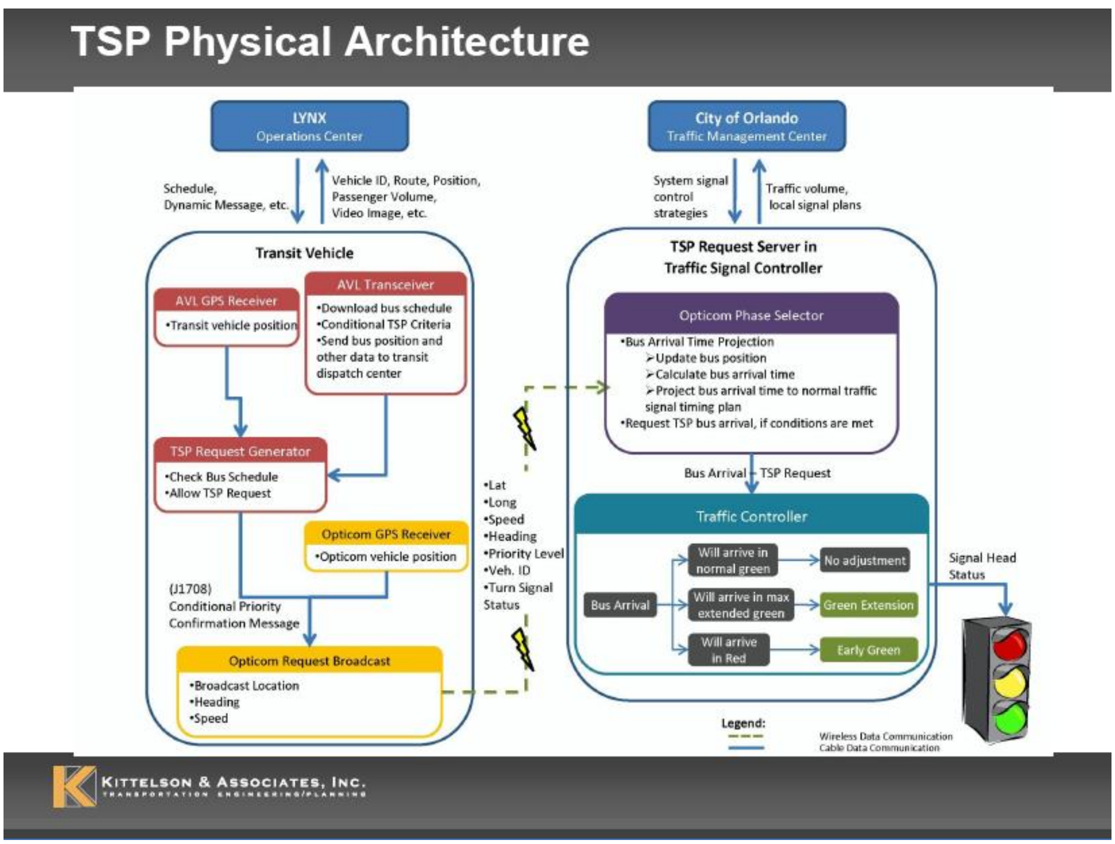

Figure 6: TSP system architecture developed by Kittleson and Associates

To establish Conditional priority, the installed AVL system granted LYNX the real-time ability to monitor on-time bus performance. The AVL updates the bus location every 30 seconds. This allows LYNX to control whether or not signal priority is granted to the TSP equipped bus. This is important for transit riders, as running ahead of schedule is considered worse than running behind. If the bus is ahead of schedule, the arriving transit riders may miss the bus if they arrive when the bus is supposed to arrive, but the bus has already left to travel to the next transit stop.

The TSP system was designed so that eight (8) seconds of green extension was the minimum interval of time necessary to warrant the use of TSP. Therefore, if the bus arrived at the signal with more than 8 seconds of green left in the cycle, the TSP would not activate. The seven signals on the I-Drive test corridor, except for the signal at Kirkman Road, operate on three different coordination patterns per day that coordinate the traffic movement on I-Drive. The signal at Kirkman Road has coordination movements on Kirkman Road (a major north-south roadway). The traffic signals at Del Verde Way and the Pedestrian signal at Sheraton run at half cycles of 75 seconds while the other signals run at cycles of 150 to 180 seconds depending on the time of day. Table 1 shows the signal cycle lengths (in seconds).

Table 1: I-Drive study area signal cycle length (seconds)
Source of data: City of Orlando

Location	Cycle Length (Seconds)
Universal Boulevard	150 to 180
Ped Signal at Sheraton	75
Kirkman Road	150 to 170
Grand National	150 to 170
Municipal Drive	150
Del Verde	75
Fun Spot Way	150

The NAZTEC TS2 controller was used in the TSP architecture. This model has two options to modify the split patterns for the signals: MAX Extend and MAX Reduce. The MAX Reduce is the maximum amount of green time that can be reduced from non-transit phases during the TSP phase (either unconditional or conditional). MAX Extend is the sum of the MAX Reduce in that same ring. This ring is the continuous loop in which the signal control organizes phases by grouping them and separating the crossing streets with time between when they operate by making the movements either sequential or adding a barrier between the conflicting movements.

As mentioned previously, OPTICOM™ Technology was chosen in the field study since the City of Orlando has the infrastructure to support this system for use in Transit Signal Priority.

The conditional priority behind schedule time was chosen as three minutes or more behind schedule as part of the system programing by the Kittleson team and LYNX. This behind schedule time was lower than the industry standard of five minutes behind schedule (Kloos, 2001) [**25**]. Therefore, it was decided to use VISSIM to simulate the corridor with five minute behind schedule TSP and compare with 3 minute behind schedule TSP.

Signal preemption hierarchy

There are several levels of signal preemption including railroad preemption, emergency vehicle preemption and transit preemption. The highest level is railroad preemption with emergency vehicle preemption the next highest and transit signal priority the lowest level of preemption. This means that if an emergency vehicle approaches a TSP equipped traffic signal, it will override any transit TSP signal that has been sent to the controller.

9. Data Collection

Data collection involved the review of past traffic studies, collection of field data by the UCF research team, and passenger data provided by LYNX. Past traffic studies were analyzed for data collected, such as traffic volumes from FDOT count stations on Kirkman Road. An Orange County Public Works 'International Drive Area Transportation Study' conducted in 2007 by the engineering firm HNTB **[26]** used Synchro files from the Orlando Urban Transportation Study (OUTS) results and model as a background. The projected traffic volumes from the HNTB study were higher than the volumes collected by the UCF research team in the field or gathered from various count stations and records. These lower volumes are a direct result of the decrease of tourist travel to Orlando starting with the economic recession of 2008. However, the area's tourist economy has been on the rebound for the past few years, with Orlando again projected to be the nation's number one tourist destination.

Field data was also collected during this research (as noted in Section 9.1) for the different TSP scenarios. Simulation analysis was performed on travel times, delay time, passenger count, and passenger delay for each of the three scenarios (No TSP, Unconditional TSP, and Conditional TSP 3 minutes behind) and a comparison of all the conditions was performed. In addition, the economic impacts of all three scenarios were evaluated.

Another source of data was passenger count information provided by LYNX. This data was reviewed to determine peak passenger volumes. Passenger count data was obtained for three bus links (8, 37, and 42) in the International Drive Corridor for intersections located between Touchstone Boulevard (now Fun Spot Way) and Universal Boulevard. The analysis of this data focused on Link 8 since this link contained the GPS Opticom buses.

9.1 Field data collected

A variety of vehicular traffic data was collected in the field. This data consisted of the following:

- Speed and volume counts (source: City of Orlando)
- Passenger count information (Automatic Passenger Counts were obtained from LYNX and hand counts were collected while riding the bus)
- Total signal delay (collected while riding the bus)
- Total passenger delay (collected while riding the bus)
- Signal split history (source: City of Orlando)
- Preemption logs (source: City of Orlando)
- Turning movement counts (collected using video and hand counts)
- Vehicle classification (source: City of Orlando)

Speed and volume counts, signal split history, and turning movement counts were used to develop the VISSIM simulation models. Passenger count information was used to determine the peak bus travel hours and peak passenger volumes. The signal delay and passenger delay were analyzed to determine the effectiveness of the TSP. The preemption logs were used to verify that the TSP was working and determine what signals were called. The vehicle classifications were used in the MOVES and AFLEET environmental programs to evaluate vehicle emissions.

9.2 Passenger counts and field data collection

Passenger counts were provided by LYNX for October 2011 to February 2012; these counts were used to determine the peak hours of passenger demand using the statistical program JMP (SAS) [**27**]. This analysis determined the peak hour for passenger demand to occur between 4:00 PM and 5:00 PM on Monday through Friday, as shown in Figure 7. To ensure field data was collected during the peak hour of passenger demand, it was decided to collect data between 3:00 PM and 7:00 PM on Tuesday through Thursday.

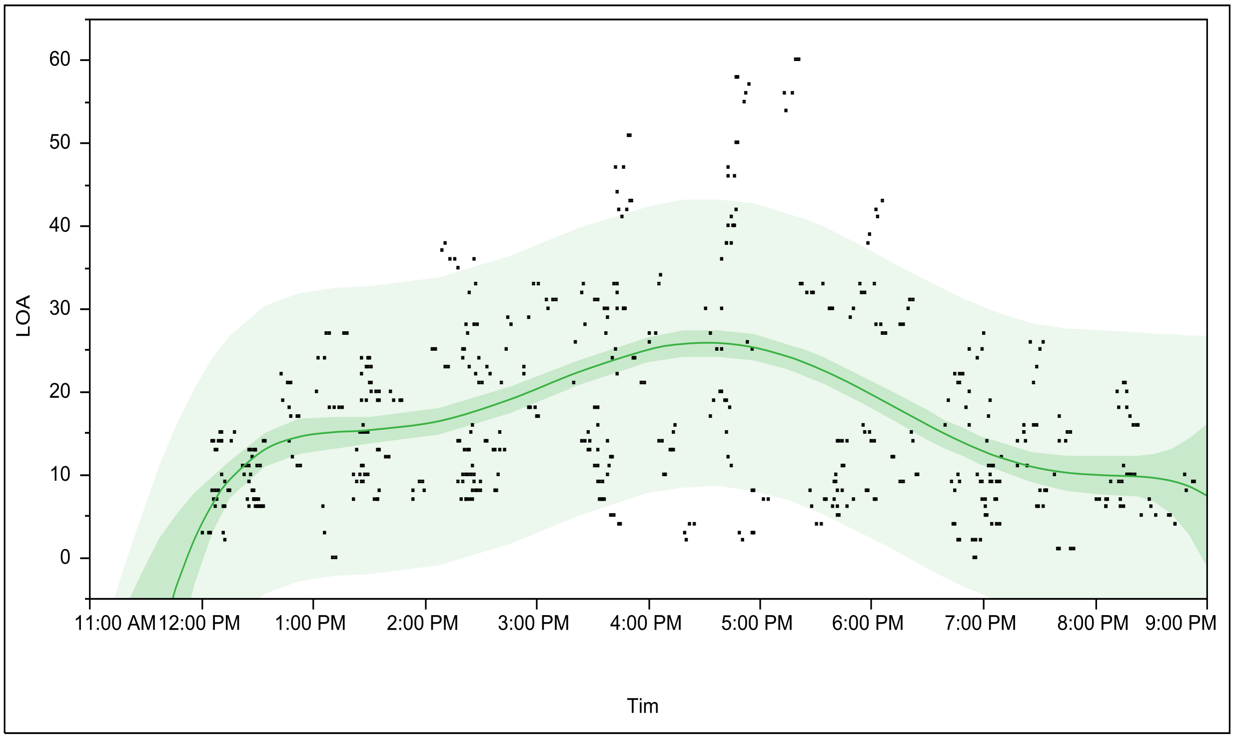

Figure 7: Passenger count data from October 31 to November 18, 2011, and from January 9 to February 1, 2012, bivariate fit of load by time (Data Source: LYNX)

Field data was collected for this research by riding a bus for the entire corridor route in each direction; this was considered one run. The data collected included the day and date, weather conditions, the location of each bus stop and signal, the bus arrival time, the time it took for the doors to open completely after arriving at each bus stop, the time it took for the doors to close completely from the moment the doors opened completely, the time it took the bus to leave the stop after the doors closed, the time of red light delay, the number of passengers that boarded and left the bus at each stop, and the total number of passengers on the bus after the bus left the bus stop. Researchers in South Florida (Pessaro and Van Nostrand, 2012) [**12**] collected bus travel time delay, but they did not collect complete passenger information as collected by the UCF research team. In addition, they did not analyze passenger delay for any potential reduction that could be attributed to TSP.

The No TSP "Before" data was collected for 31 runs eastbound (EB) and westbound (WB) from March 6 to April 10, 2013. Unconditional TSP data was collected for 10 runs EB and WB from May 6 to May 8, 2013. Unconditional data was limited because the TSP system was implemented by the City of Orlando shortly and it was not possible to wait for sufficient runs during Unconditional phase. Conditional TSP "After" data was collected for 11 runs EB and WB from June 3 to June 13, 2013 (additional data was collected in August and September 2013).

9.3 Discussion of data collection methods

Traffic volumes and vehicle classifications were collected by a team of UCF students using pneumatic tubes at several locations along the corridor (Figure 8).

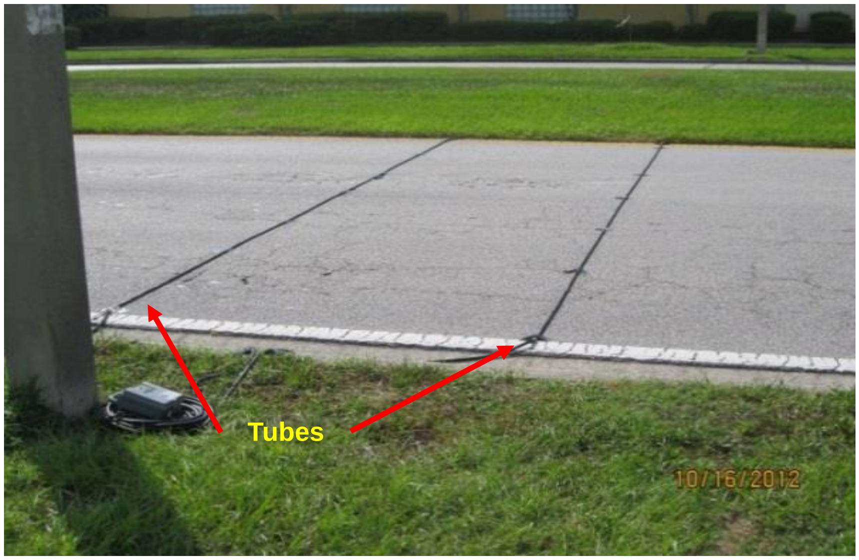

Figure 8: Pneumatic tubes used for vehicle classifications near Fun Spot Way (formerly Touchstone Drive) on northbound I-Drive

In addition, turning movement counts were collected at Touchstone Drive, Municipal Drive, Grand National Drive and Universal Boulevard by either using a Jamar count board or videotaping (Figures 9 and 10).

Figure 9: Turning movement counts using hand held board (Jamar)

Figure 10: Videotaping turning movements at Universal Boulevard and I-Drive (located at southwest corner)

The City of Orlando camera on the mast arm support at Kirkman Road was used to record turning movements at this intersection (Figure 11).

Figure 11: Traffic camera on top of mast arm support at Kirkman road and I-Drive

9.4 Signal timing data collection efforts (split history)

Signal timing information was obtained from the City of Orlando TMC and used in the development of the VISSIM simulation modeling for this corridor. It was very important to come up with an optimized model for signal timing, which minimized disruptions to the intersecting traffic at equipped TSP signalized intersections. Two intersections along the test corridor (Universal Boulevard and Kirkman Road) have a high volume of traffic and any additional delay would severely impact the roadway network. A sample of the split history, which is recorded and stored by the City of Orlando Traffic Engineering Department at their TMC, is shown in Figure 12.

Split History

10/17/2012

ID: 370

Name: Grand National Dr & International Dr

Begin Date/Time: 10/16/2012 4:15 pm **End Date/Time:** 10/16/2012 6:45 pm

DateTime		Pattern	Cycle	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8
10/16/2012	16:15 PM	15	170	19	88	0	63	0	107	16	47
10/16/2012	16:18 PM	15	170	18	92	0	60	0	110	13	47
10/16/2012	16:21 PM	15	170	24	83	0	63	0	107	15	48
10/16/2012	16:23 PM	15	170	0	107	0	63	0	107	16	47
10/16/2012	16:26 PM	15	170	23	84	0	63	12	95	13	50
10/16/2012	16:29 PM	15	170	18	89	0	63	0	107	16	47
10/16/2012	16:32 PM	15	170	24	83	0	63	15	92	14	49
10/16/2012	16:35 PM	15	170	24	83	13	50	14	93	16	47
10/16/2012	16:38 PM	15	170	23	84	12	51	0	107	16	47
10/16/2012	16:40 PM	15	170	18	97	0	55	0	115	13	42
10/16/2012	16:43 PM	15	170	24	83	12	51	13	94	16	47
10/16/2012	16:46 PM	15	170	24	83	14	49	0	107	16	47
10/16/2012	16:49 PM	15	170	24	83	0	63	0	107	16	47
10/16/2012	16:52 PM	15	170	24	83	13	50	0	107	16	47
10/16/2012	16:55 PM	15	170	24	83	12	51	0	107	16	47
10/16/2012	16:57 PM	15	170	24	83	0	63	0	107	16	47
10/16/2012	17:00 PM	15	170	18	89	13	50	0	107	16	47
10/16/2012	17:03 PM	15	170	24	83	14	49	0	107	16	47
10/16/2012	17:06 PM	15	170	24	83	14	49	0	107	16	47
10/16/2012	17:09 PM	15	170	22	85	13	50	22	85	16	47
10/16/2012	17:12 PM	15	170	24	83	12	51	16	91	16	47
10/16/2012	17:14 PM	15	156	21	73	0	62	15	79	15	47
10/16/2012	17:17 PM	15	168	18	89	0	61	0	107	14	47
10/16/2012	17:20 PM	15	170	24	83	0	63	15	92	16	47
10/16/2012	17:23 PM	15	156	21	73	0	62	0	94	15	47
10/16/2012	17:26 PM	15	160	21	77	13	49	0	98	15	47
10/16/2012	17:29 PM	15	156	21	73	13	49	0	94	15	47
10/16/2012	17:32 PM	15	160	21	78	12	49	0	99	14	47
10/16/2012	17:34 PM	15	170	24	83	0	63	13	94	16	47
10/16/2012	17:37 PM	15	155	18	76	0	61	11	83	14	47
10/16/2012	17:40 PM	15	160	21	77	0	62	12	86	15	47

Figure 12: Split history sample for International Drive (source: City of Orlando)

10. Data Exploration and Statistical Analysis

10.1 Data exploration

Data exploration was performed on the data collected in the field for each TSP scenario: No TSP, Unconditional TSP, and Conditional TSP. The traffic signal red delay and passenger stop delay were analyzed, as shown in Table 2 for the eastbound direction and Table 3 for the westbound direction. The values shown are averages, with times shown in seconds. The "passengers on board" parameter represents the average number of passengers on the bus at each location.

Table 2: I-Drive eastbound – signal red delay, average passenger delay, and average passengers on board

Node	Distance (Ft)	Signal Location	TSP Signal	EB Average Signal Red Delay Sec			EB	EB Average Passenger Delay Sec			EB Average Passengers On Board		
				No-TSP	Unconditional	Conditional	Bus Stop #	No-TSP	Unconditional	Conditional	No-TSP	Unconditional	Conditional
1	0						1	12.0	11.4	14.5	32.9	31.8	38.8
2	22	Universal	TSP	14.6	14.0	16.7							
3	770						2	23.1	13.6	20.6	34.3	31.3	42.6
4	1716	Kirkman	Non TSP	37.7	32.0	20.8							
5	2529	Grand National	TSP	32.3	34.3	33.6							
6	2783						3	18.7	15.1	16.0	36.5	33	44.1
7	3810	Municipal	TSP	3.7	0.0	4.5							
8	4014						4	11.3	10.7	6.5	36.8	33.6	44.9
9	4533	Del Verde Way	TSP	1.0	0.8	0.0							
10	5096						5	1.3	1.5	0.0	36.8	33.6	44.9
11	5755	Fun Spot	TSP	10.1	8.0	2.7							
12	5966						6	5.8	7.3	2.2	36.7	33.1	45.2
13	6494	Altamira	Non TSP	44.5	20.4	59.5							
14	6758						7	9.6	10.6	9.5	37.1	33.9	45.3
15	9240						8	26.3	15.1	13.5	37.6	32.7	44.8
16	9821	Oak Ridge	Non TSP	35.4	30.9	33.9							
17	10190						9	18.1	13.2	13.5	37.9	33.1	44.8
		Total Corridor TSP		61.8	57.1	57.6							
		Total Corridor Non-TSP		117.5	83.3	114.3							
		Total Corridor		179.3	140.4	171.9	**Total Corridor**	126.1	98.5	96.3	36.3	32.9	43.9

Table 3: I-Drive westbound – signal red delay, average passenger delay, and average passengers on board

Node	Distance (Ft)	Signal Location	TSP Signal	WB Average Signal Red Delay Sec			WB	WB Average Passenger Delay Sec			WB Average Passengers On Board		
				No-TSP	Unconditional	Conditional	Bus Stop #	No-TSP	Unconditional	Conditional	No-TSP	Unconditional	Conditional
18	0						10	14.7	11.7	11.9	15.0	12.2	16.6
19	304	Oak Ridge	Non TSP	22.0	24.3	8.0							
20	1020						11	26.2	15.8	10.7	16.6	13.1	17.3
21	3408						12	8.2	4	3.5	16.3	12.9	17.6
22	3692	Altamira	Non TSP	14.9	5.8	21.5							
23	4295						13	6.7	5.2	4.7	16.6	13.4	18.7
24	4397	Fun Spot	TSP	8.3	17.1	18.5							
25	4397	Del Verde Way	TSP	1.7	0.0	0.0							
26	6230	Municipal	TSP	5.8	0.0	4.9							
27	6389						14	6.2	9.1	11.4	15.8	12.8	19.4
28	7445						15	20.9	22.3	22.9	17.5	12.6	21.7
29	7498	Grand National	TSP	27.4	43.2	41.7							
30	8237	Kirkman	Non TSP	33.2	43.4	32.5							
31	9346						16	11.1	9	9.1	17.7	12.7	22.8
32	9979	Universal	TSP	47.4	23.4	40.7							
33	10243						17	11.6	11.3	11.2	17.2	12.3	22.8
		Total Corridor TSP		90.7	83.7	105.9							
		Total Corridor Non-TSP		70.1	73.5	61.9							
		Total Corridor		160.8	157.2	167.8	**Total Corridor**	105.4	88.4	85.4	16.6	12.8	22.4

10.2 Signal red delay, average passenger delay, and average passengers on board

10.2.1 Eastbound direction

Compared to No TSP, the average signal delay at the TSP equipped signals was reduced by 4.7 seconds, or 7.6%, with the Unconditional TSP, and by 4.2 seconds, or 6.8%, with the Conditional TSP. During Unconditional TSP, the average delay was reduced at four of the five TSP signals; during Conditional TSP, the average delay was reduced at two of the five signals. The average passenger delay and signal delay for the entire corridor was lower for both Unconditional and Conditional TSP.

10.2.2 Westbound Direction

Compared to No TSP, the average signal delay at the TSP equipped signals was reduced by 7 seconds, or 7.7%, with the Unconditional TSP. The average signal delay increased with the Conditional TSP. For both Unconditional and Conditional TSP, the average signal delay was reduced at three of the five TSP signals. The average passenger delay for the entire corridor was lower for both Unconditional and Conditional TSP.

10.3 Unconditional TSP confirmation

Preemption confirmation logs were recorded by the City of Orlando TMC. These logs were reviewed to verify that the Unconditional TSP was operational, as well as when the TSP equipped signals were called during the Unconditional TSP scenario. During this scenario, the traffic signals were called any time the bus was approaching the equipped signal, even if the bus was not behind schedule. Bus data was collected for the Unconditional TSP on May 6, 7, and 8, 2013. The preemption logs for these dates, as well as other dates when the Unconditional TSP was active, are shown in Table 4. The preemption logs contain all calls to the traffic signal controller; these calls include TSP as well as emergency preemption. Data was generally recorded from 6:00 AM to 12 midnight each day. For each day, the number of TSP calls for each intersection was divided by the total number of preemption calls to obtain a percentage. It is important to note that if the signal is in a green phase when the bus approaches, the TSP is not called. The table shows that the pedestrian signal at the Sheraton had the highest percentage of unconditional TSP calls. Del Verde was the TSP signal with the most Unconditional TSP calls and Universal Boulevard had the least calls.

In May 2014, it was discovered by City of Orlando staff that Fun Spot Way stopped recording low priority preemptions (or TSP activations) in early May 2013. This issue was attributed to possible communication failure of preemption notification between the signal and the TMC.

Table 4: Unconditional TSP confirmation (source of data: City of Orlando preemption logs)

TSP Intersection	TSP/Preemption 05-01-13	%TSP	TSP/Preemption 05-02-13	%TSP	TSP/Preemption 05-03-13	%TSP	TSP/Preemption 05-04-13	%TSP
Fun Spot Way	14/14	100.00%	15/17	88.24%	17/17	100.00%	4/4	100.00%
Del Verde Way	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Ped Signal	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Municipal	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Grand National	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Kirkman	0/3	0.00%	0/10	0.00%	0/2	0.00%	0/3	0.00%
Universal	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A

TSP Intersection	TSP/Preemption 05-05-13	%TSP	TSP/Preemption 05-06-13*	%TSP	TSP/Preemption 05-07-13*	%TSP	TSP/Preemption 05-08-13*	%TSP
Fun Spot Way	No Data	N/A	10/10	100.00%	4/7	57.14%	0/4	0.00%
Del Verde Way	No Data	N/A	19/38	50.00%	13/25	52.00%	24/46	52.17%
Ped Signal	No Data	N/A	21/22	95.45%	10/10	100.00%	17/22	77.27%
Municipal	No Data	N/A	0/13	0.00%	0/13	0.00%	0/24	0.00%
Grand National	No Data	N/A	0/14	0.00%	0/11	0.00%	0/26	0.00%
Kirkman	0/10	0.00%	0/3	0.00%	0/8	0.00%	0/13	0.00%
Universal	No Data	N/A	29/29	100.00%	14/14	100.00%	27/35	77.14%

TSP Intersection	TSP/Preemption 05-09-13	%TSP	TSP/Preemption 05-15-13	%TSP	TSP/Preemption 05-16-13	%TSP	TSP/Preemption 05-22-13	%TSP
Fun Spot Way	0/1	0.00%	No Data	N/A	No Data	N/A	No Data	N/A
Del Verde Way	12/25	48.00%	16/27	59.26%	5/7	71.43%	5/10	50.00%
Ped Signal	15/16	93.75%	12/12	100.00%	3/3	100.00%	5/7	71.43%
Municipal	16/16	100.00%	0/23	0.00%	0/5	0.00%	0/11	0.00%
Grand National	0/19	0.00%	12/35	34.29%	3/9	33.33%	5/18	27.78%
Kirkman	0/5	0.00%	0/3	0.00%	No Data	N/A	0/13	0.00%
Universal	22/24	91.67%	10/46	21.74%	3/9	33.33%	0/22	0.00%

TSP Intersection	TSP/Preemption 05-29-13	%TSP	TSP/Preemption 05-30-13	%TSP
Fun Spot Way	0/1	0.00%	0/2	0.00%
Del Verde Way	2/2	100.00%	4/5	80.00%
Ped Signal	No Data	N/A	1/1	100.00%
Municipal	0/1	0.00%	0/4	0.00%
Grand National	3/9	33.33%	1/4	25.00%
Kirkman	No Data	N/A	No Data	N/A
Universal	0/2	0.00%	0/6	0.00%

Table 5: Conditional TSP confirmation (source of data: City of Orlando preemption logs)

TSP Intersection	TSP/Preemption 06-03-13*	%TSP	TSP/Preemption 06-05-13	%TSP	TSP/Preemption 06-10-13	%TSP	TSP/Preemption 06-11-13	%TSP
Fun Spot Way	0/1	0.00%	No Data	N/A	0/2	0.00%	0/1	0.00%
Del Verde Way	9/20	45.00%	2/3	66.67%	2/5	40.00%	3/5	60.00%
Ped Signal	10/11	90.91%	2/2	100.00%	1/1	100.00%	2/2	100.00%
Municipal	0/9	0.00%	0/5	0.00%	0/3	0.00%	0/3	0.00%
Grand National	9/20	45.00%	1/5	20.00%	1/4	25.00%	2/5	40.00%
Kirkman	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Universal	0/24	0.00%	0/6	0.00%	0/7	0.00%	0/6	0.00%

TSP Intersection	TSP/Preemption 06-12-13*	%TSP	TSP/Preemption 06-13-13*	%TSP	TSP/Preemption 06-18-13	%TSP	TSP/Preemption 06-19-13	%TSP
Fun Spot Way	No Data	N/A	No Data	N/A	No Data	N/A	0/4	0.00%
Del Verde Way	8/13	61.54%	1/1	100.00%	6/11	54.55%	7/12	58.33%
Ped Signal	6/8	75.00%	No Data	N/A	4/4	100.00%	3/3	100.00%
Municipal	0/9	0.00%	No Data	N/A	0/5	0.00%	0/13	0.00%
Grand National	6/17	35.29%	0/2	0.00%	4/9	44.44%	3/20	15.00%
Kirkman	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Universal	0/23	0.00%	2/4	50.00%	1/13	7.69%	7/20	35.00%

TSP Intersection	TSP/Preemption 07-08-13*	%TSP	TSP/Preemption 07-10-13	%TSP	TSP/Preemption 08-27-13 *	%TSP	TSP/Preemption 08-29-13*	%TSP
Fun Spot Way	No Data	N/A	No Data	N/A	No Data	N/A	0/2	0.00%
Del Verde Way	11/16	68.75%	4/7	57.14%	1/3	33.33%	6/14	42.86%
Ped Signal	5/7	71.43%	2/4	50.00%	2/3	66.67%	8/10	80.00%
Municipal	0/13	0.00%	0/9	0.00%	0/5	0.00%	0/11	0.00%
Grand National	5/23	21.74%	3/10	30.00%	2/6	33.33%	7/21	33.33%
Kirkman	No Data	N/A	No Data	N/A	No Data	N/A	No Data	N/A
Universal	4/35	11.43%	4/16	25.00%	5/11	45.45%	5/25	20.00%

TSP Intersection	TSP/Preemption 09-04-13*	%TSP	TSP/Preemption 09-09-13*	%TSP	TSP/Preemption 09-10-13*	%TSP
Fun Spot Way	No Data	N/A	0/4	0.00%	No Data	N/A
Del Verde Way	1/3	33.33%	1/4	25.00%	0/1	0.00%
Ped Signal	1/2	50.00%	2/2	100.00%	1/2	50.00%
Municipal	0/1	0.00%	0/2	0.00%	0/1	0.00%
Grand National	1/3	33.33%	2/3	66.67%	1/3	33.33%
Kirkman	No Data	N/A	No Data	N/A	No Data	N/A
Universal	0/0	0.00%	0/6	0.00%	0/3	0.00%

10.4 Conditional TSP confirmation

Preemption call log confirmations collected by the Orlando TMC were reviewed to verify that the Conditional TSP was operational and to see when the TSP equipped signals were called during the Conditional TSP scenario. During this scenario, the traffic signals were called only if the bus was three minutes or more behind schedule. Bus data was collected for the Conditional TSP on June 6, 12, and 13, 2013; August 27 and 29, 2013; and September 4, 9, and 10, 2013. The preemption logs for these dates, as well as other dates when the Conditional TSP was active, are shown in Table 5. For each day, the number of TSP calls for each intersection was divided by the total number of preemption calls to obtain a percentage. The Del Verde signal received the most Conditional TSP calls while the signal at Universal Boulevard received the least, except for the signal at Fun Spot Way, which had limited data in the preemption logs and did not receive any TSP requests due to the communication issue the signal developed in May 2013.

These preemption logs showed that the TSP did not work consistently at all of the TSP signals for both Unconditional and Conditional TSP. This led the team to review the difficulties encountered during field data collection and the need for other methods for evaluation, specifically micro-simulation (VISSIM). Unpredictable real world situations furthered the conclusion that micro-simulation would be a more accurate method for TSP evaluation in this research.

10.5 Bus route trajectories

In order to better understand how TSP affected bus travel, bus route trajectories were drawn using the average bus speed and average red signal and stop delays. The average bus speed was calculated by subtracting the total delay from the average route duration (to obtain the time not stopped) and then dividing the corridor distance by this result for each TSP scenario in each direction. As an example, for eastbound No TSP, the total delay is 305.5 seconds and the average route duration is 748.26 seconds, with a corridor distance of 10,190 feet; therefore, the average bus speed is 10,190 feet/(748.26 seconds – 305.5 seconds), which equals 10,190 feet/442.8 seconds, or an average speed of 23 feet per second (fps). The following speeds were obtained by this method and are shown in figures 13 and 14:

- Eastbound No TSP speed = 23 fps
- Eastbound Unconditional speed = 24.7 fps
- Eastbound Conditional speed = 25.8 fps
- Westbound No TSP speed = 24 fps
- Westbound Unconditional speed = 29.5 fps
- Westbound Conditional speed = 26.3 fps

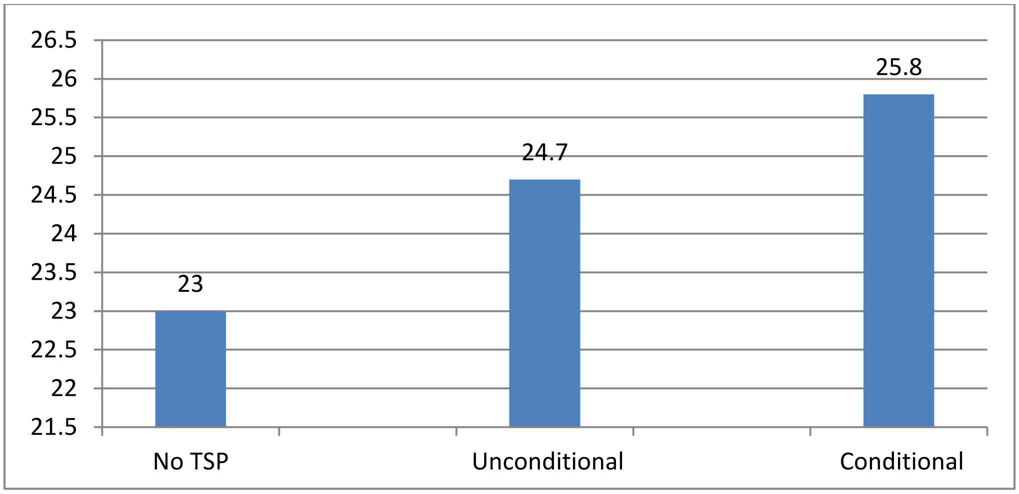

Figure 13: Eastbound I-Drive Speeds (ft/sec)

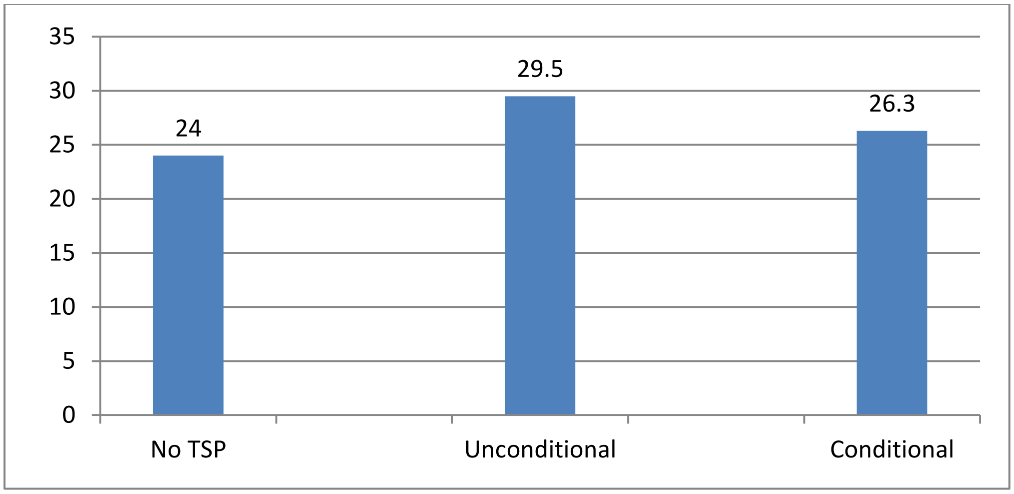

Figure 14: Westbound I-Drive Speeds (ft/sec)

The average bus trajectories for No TSP, Unconditional TSP and Conditional TSP are shown in Figures 15 and 16 for the eastbound and westbound directions, respectively. The eastbound route is 10,190 feet long, with the TSP signals concentrated in the corridor segment from 0 feet to 5,755 feet. The westbound route is 10,243 feet long, with the TSP signals concentrated in the corridor segment from 4,295 feet to 9,979 feet.

The eastbound trajectories show that Unconditional TSP reduced average travel time through the TSP segment by 41.2 seconds, or 9.9%, compared to No TSP, and Conditional TSP reduced the travel time through this same segment by 56.9 seconds, or 13.7%. The westbound trajectories show that Unconditional TSP reduced travel time through the TSP segment by 38.6 seconds, or 9.7%, compared to No TSP, and Conditional TSP reduced the travel time through this same segment by 0.9 seconds, or 0.2%.

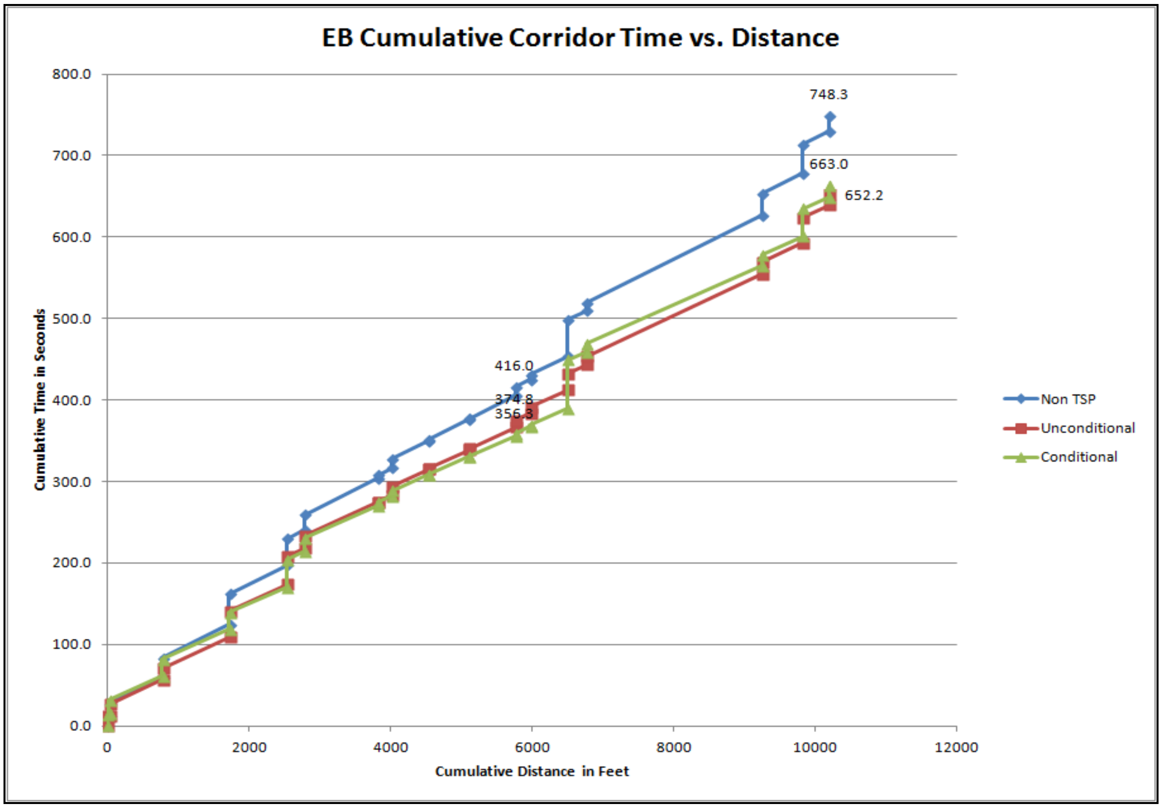

Figure 15: Eastbound bus trajectories for No TSP, Unconditional TSP, and Conditional TSP

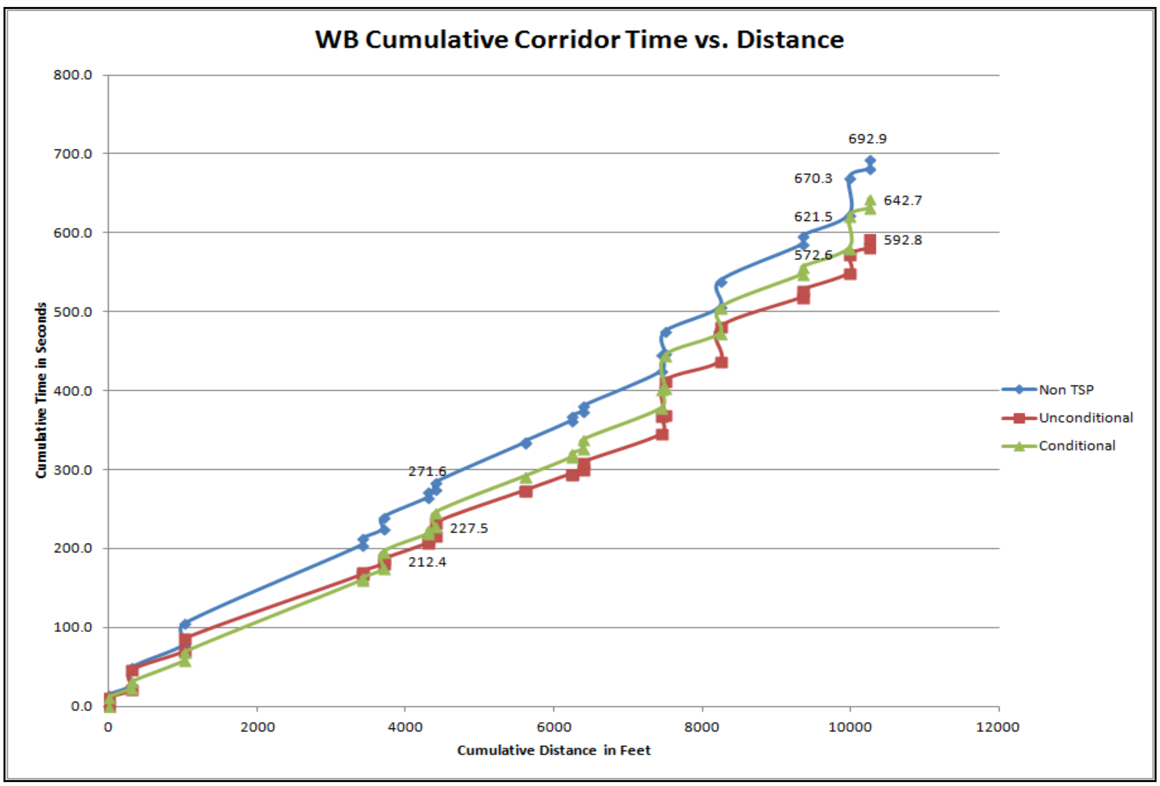

Figure 16: Westbound bus trajectories for No TSP, Unconditional TSP, and Conditional TSP

10.6 Simple statistical analysis

In an effort to validate the bus data collected and determine if either Unconditional TSP or Conditional TSP was better than No TSP, several statistical methods were used for data evaluation including Two Factor ANOVA and Linear Regression in MINITAB. However, model development found poor results in the use of Two Factor ANOVA. This led to the use of linear regression as the results were more consistent and appeared more accurate as models were developed. The eastbound and westbound red signal and pedestrian delay were evaluated using linear regression. The statistical program Minitab 17, developed by Minitab, Inc. [**28**] was used for this analysis. The Dunnett Test with Control (Dunnett, 1955) **[29]** was used. The data, including the red signal delay in seconds and the bus passenger delay in seconds was prepared using Microsoft Excel. This data preparation is shown in Appendix A.

After preparation, the data was analyzed and both Unconditional TSP and Conditional TSP were compared with the control scenario (No TSP) to determine if Unconditional and Conditional TSP were effective in reducing bus travel times and increasing adherence to the bus schedules. The analysis performed involved the review of p-values, F-values, R-Squared and the Variance Inflation Factor (VIF). Developed models are considered significant if the p-value is equal to or smaller than $\alpha = 0.05$ and insignificant if the p-value is greater than $\alpha = 0.05$. The VIF is a measure of how much of an estimated regression coefficient increases due to collinearity, where collinearity is the approximate linear relationship between two variables. This value should be less than 5; if the VIF is greater than 5, then there is a chance of multi-collinearity.

Transformation of data

Several iterations of data analysis using MINITAB found that the data points were scattered on the probability plot and required normalization. Several transformation methods were considered including square root, reciprocal and ln. However, the reciprocal and ln could not be used since the data collected contained zero (0) delay values in the red signal and passenger delay data. Therefore, the square root transformation was performed to normalize the red signal and passenger delay data in order to run the linear regression analysis.

Transformation of the red signal delay eastbound (seconds) was performed with normalizing the delay data (seconds) by taking the square root of the delay. The name of the equation is shown as square root delay in MINITAB but it is the transformed delay data. This is the red signal delay eastbound at each signal location. The following are examples of the regression equations for red signal delay eastbound.

<u>LOCATION (L)</u>

Del Verde (EB) Square Root Delay = 0.276 + 1.622 uni*cond2 - 1.572 kirk*cond2

Fun Spot (EB) Square Root Delay = 1.366 + 1.622 uni*cond2 - 1.572 kirk*cond2

Grand Nat. (EB) Square Root Delay = 4.745 + 1.622 uni*cond2 - 1.572 kirk*cond2

Kirkman (EB) Square Root Delay = 5.319 + 1.622 uni*cond2 - 1.572 kirk*cond2

Municipal (EB) Square Root Delay = 0.562 + 1.622 uni*cond2 - 1.572 kirk*cond2

Universal (EB) Square Root Delay = 2.453 + 1.622 uni*cond2 - 1.572 kirk*cond2

Note that "uni" is short for Universal Boulevard and "kirk" is short for Kirkman Boulevard.

Figures 17, 18, 19, and 20 show the plots for eastbound and westbound red signal delay and passenger delay. The full MINITAB outputs are included in Appendix A.

Red signal delay eastbound

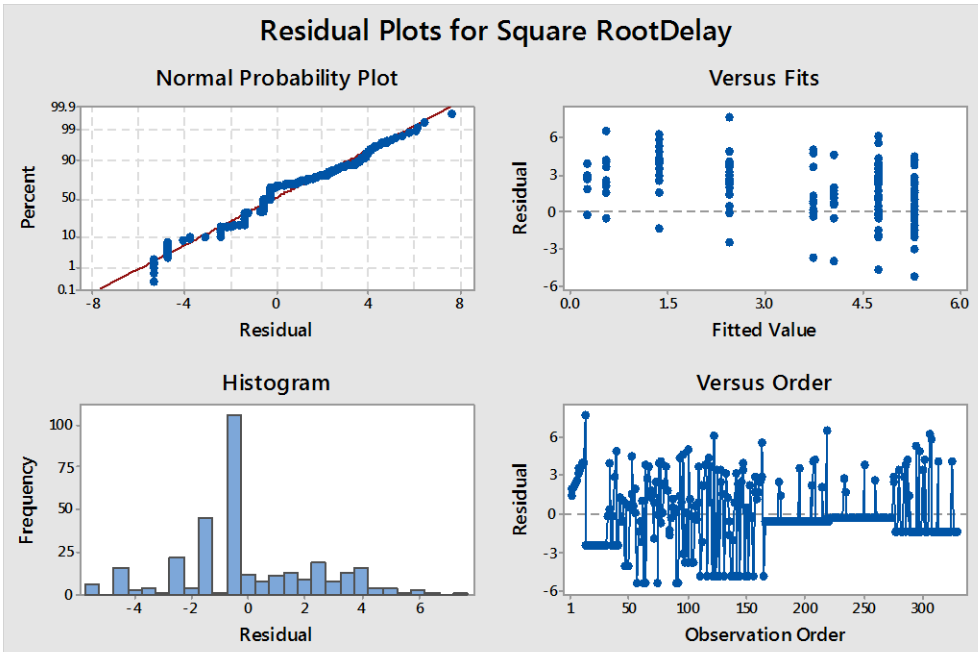

Figure 17: Residual plots for square root signal delay - eastbound

Red signal delay westbound

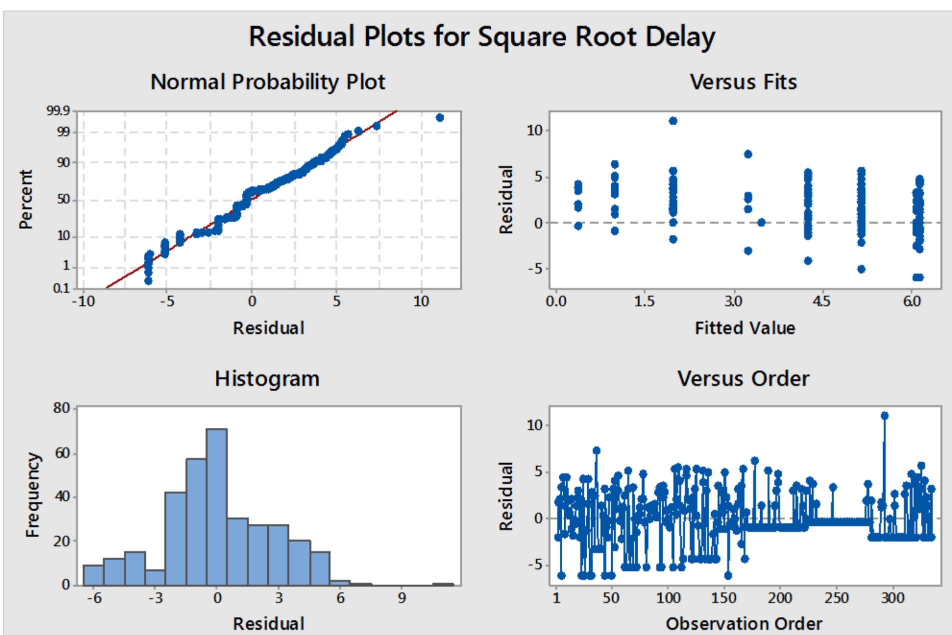

Figure 18: Residual plots for square root signal delay - westbound

<u>Passenger delay eastbound</u>

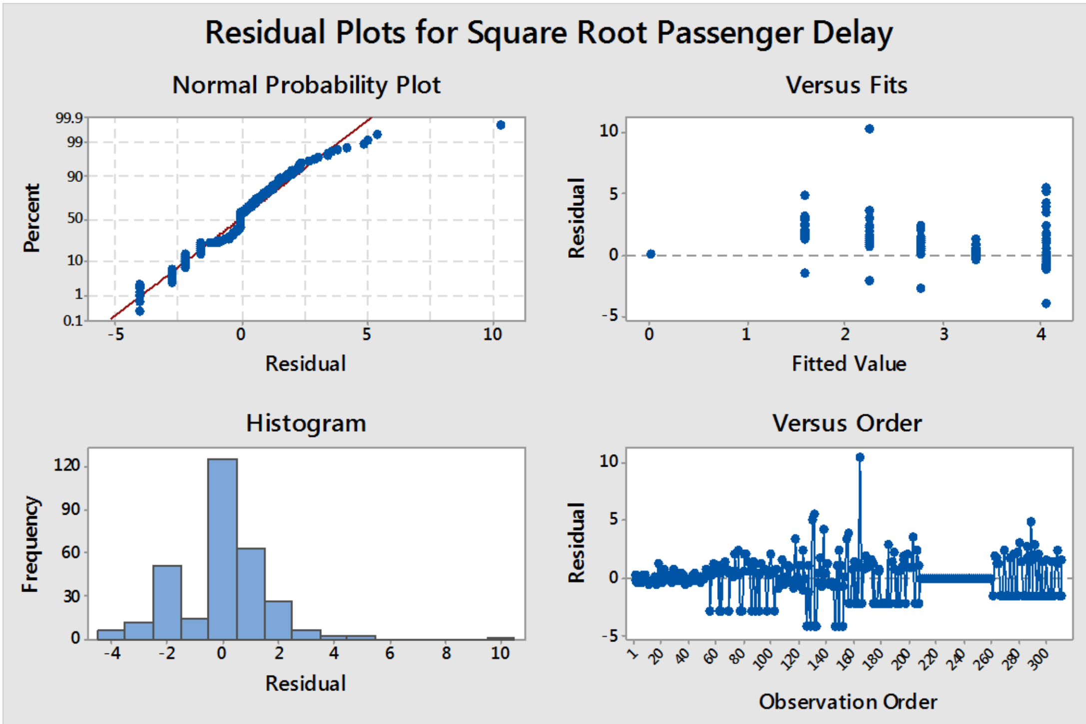

Figure 19: Residual plots for square root passenger delay - eastbound

<u>Passenger delay westbound</u>

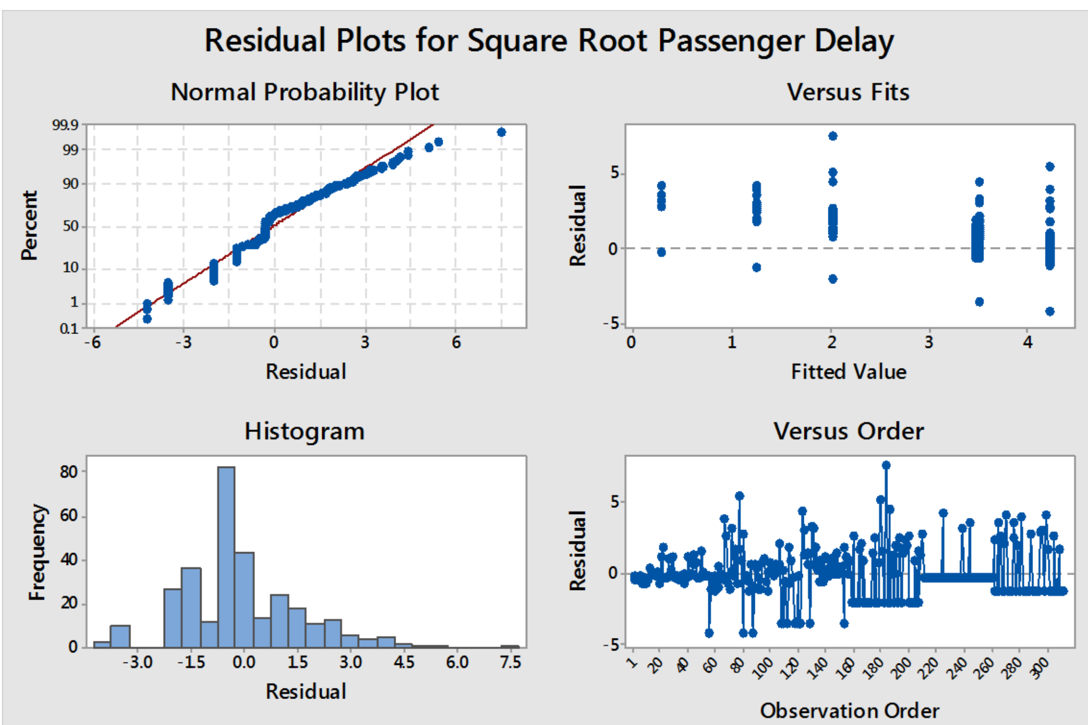

Figure 20: Residual plots for square root passenger delay - westbound

The probability plots in the preceding figures show that the transformed data is normally distributed in all four plots; this is also shown in the histograms. The R^2 results for all four residual plots are summarized in Table 6 (the full analysis is shown in Appendix A). The R^2 values were improved after transformation from the previous linear regression analysis, where the previous values were in the low .30's. VIF values were all below 5.

Table 6: R^2 results for all four residual plots

Description	R^2
Red signal delay (EB)	.3761
Red Signal delay (WB)	.3799
Passenger delay (EB)	.4006
Passenger delay (WB)	.3831

The small sample sizes probably had an adverse effect on the R^2 values, causing them to be .40 or lower. In addition, both the red signal and passenger delay data had data points with zero values (0 seconds). These zero values represent when the bus did not stop at a signal or did not stop at the bus stop and might have affected the statistical analysis. The uncertainty of the statistical variability of the collected data, represented by the low R^2 values, led to the use of VISSIM simulation to determine if Conditional TSP was beneficial to the transit system.

10.7 Summary of data exploration

The focus of this data exploration was to determine whether TSP improved bus travel time and schedule adherence in the TSP corridor by analyzing route durations and delay times. Both Unconditional and Conditional TSP were evaluated; the Unconditional TSP always provides signal priority for the bus, whereas the Conditional TSP only provides priority when the bus is behind schedule by three minutes or more, thereby reducing the chance of the bus reaching a stop too early.

The data exploration for the Unconditional TSP showed that four of the five TSP signals experienced an average delay reduction in the eastbound direction, and three of the signals experienced an average delay reduction in the westbound direction. For Conditional TSP, two of the TSP signals experienced an average delay reduction in the eastbound direction, and three of the signals experienced an average delay reduction in the westbound direction.

Bus route trajectories based on the average speed through the corridor showed that both Unconditional and Conditional TSP reduced the average travel time through the segment of the corridor where the TSP signals were concentrated. The eastbound direction experienced a 9.9% travel time reduction during Unconditional TSP and a 13.7% travel time reduction during Conditional TSP through this corridor segment compared to No TSP. For the same corridor segment, the westbound direction experienced a 9.7% travel time reduction during Unconditional TSP and a 0.2% travel time reduction during Conditional TSP compared to No TSP.

Unconditional TSP was effective in reducing signal delay and travel time for both the east and westbound directions for the I-Drive corridor. The conditional TSP was effective for reducing signal delay and travel time in the eastbound direction, but not in the westbound direction. Additionally, variations in travel times were reduced for both TSP scenarios and the very high travel times experienced by buses with No TSP were reduced for both TSP scenarios in both directions.

One issue that was encountered in the westbound direction was that the signal at Grand National is only about 745 feet away from the signal at Kirkman. This close proximity causes the Grand National signal to be clearly affected by westbound traffic congestion at Kirkman. Other signals along the corridor are spaced further apart. For example, the separation between the signals at Grand National and Municipal Drive intersections is 1260 feet. This distance, nearly ¼ of a mile, is the minimum separation distance that the city of Orlando uses between most traffic signals. This minimum distance is used because signals that are placed closer than ¼ mile can influence each other by increasing delays as the upstream signal turns green when the downstream signal is red, causing traffic to back up through the green signal intersection.

The simple statistical analysis showed that it could not be stated with certainty that there was a significant discernable difference between the No TSP and the Unconditional TSP scenarios, as well as between the No TSP and the Conditional TSP scenarios. One contributing factor to this result might have been the low number of samples (31 data points for No TSP, 10 for Unconditional and 11 for Conditional). These small sample sizes probably affected the R^2 values, causing all these values to be .40 or lower. The inconsistencies in some of the results might also be due to the difficulty in having a fully controlled real world experiment. Additionally, the multiple data points collected with zero values might have affected the statistical analysis.

The inability to be able to state with certainty that there was a difference between No TSP and TSP led to the use of micro-simulation to determine if Conditional TSP was beneficial to the transit system. Micro-simulation was also used to evaluate a second Conditional TSP scenario. This micro-simulation is the subject of the next chapter in this research report.

11. Micro-Simulation Modeling (VISSIM)

VISSIM [**1**] is a simulation model that can be used to accurately model traffic including transit operations. In this research, it was used to model different TSP scenarios related to transit operations and its effect on signal operations at the intersections on I-Drive. The major intersections studied were at Universal Boulevard and Kirkman Road, with a medium sized intersection at Grand National and a smaller one at Municipal Drive. The other three intersections in the test corridor are minor and transit priority operations would rarely affect these because of low side street volumes. However, all seven intersections were modeled and analyzed in VISSIM.

In the test corridor, TSP was used in three different scenarios: No TSP, Unconditional TSP, and Conditional TSP 3 minutes behind. These scenarios were modeled in VISSIM, along with a fourth scenario: Conditional TSP 5 minutes behind. This scenario was chosen in order to compare different Conditional TSP scenarios, and 5 minutes was chosen since that is the industry standard (Kloos, 2002) [**25**].

11.1 Scope of modeling

The TSP corridor was modeled in VISSIM utilizing field data collected, information from the city of Orlando and information from the Kittleson study (Freeman, 2013) [**13**] to accurately simulate the real corridor. A sample of the VISSIM model developed using the available data is shown in Figure 21. This model was used to determine the average speed profile, the average travel time, turning movement counts at all signalized intersections, and arterial performance along the corridor.

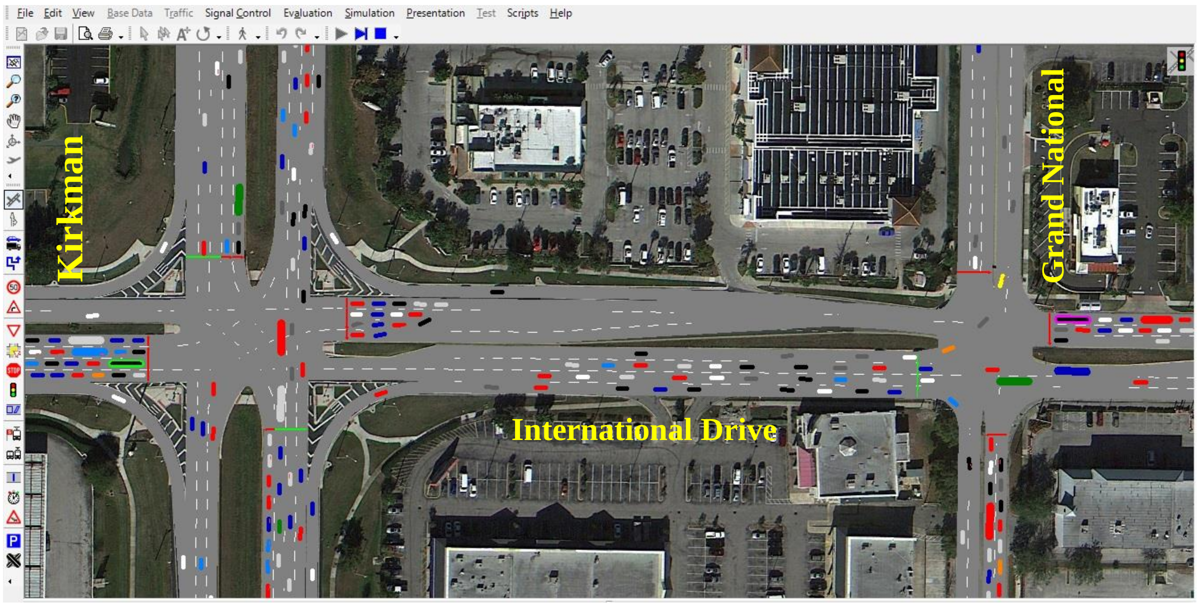

Figure 21: Kirkman and Grand National intersections on I-Drive coded in VISSIM

11.2 Model calibration and validation

The No TSP VISSIM Model was developed for the PM peak period (3:00PM – 7:00 PM) on I-Drive. First, it was necessary to determine the minimum number of VISSIM runs required, using the formula shown below. This formula was obtained from the California Department of Transportation (CALTRANS, 2002) [**31**].

$$N = (2 * t_{0.025,\ N-1} * S/R)^2$$

Where the input variables are:

- N = the minimum required number of runs,
- $t_{0.025,\ N-1}$ = student t-test (two-sided error) with (N-1) degree of freedom,
- S = standard deviation,
- R = 95% confidence interval for the true mean.

** The number of runs (N = 10) was used as a start to calculate later for the required (N) using the mean travel time (389.71 sec), S (12.32), $t_{0.025,\ N-1}$ (2.3), and R (7.64) from those initial 10 runs.

Initially, 10 runs were performed to determine how many actual runs were needed based on the **N** equation above. The average (mean) of travel times and standard deviation for these (10) runs were used to determine that the minimum number of runs required for a 95% confidence interval was **N = 55 runs**.

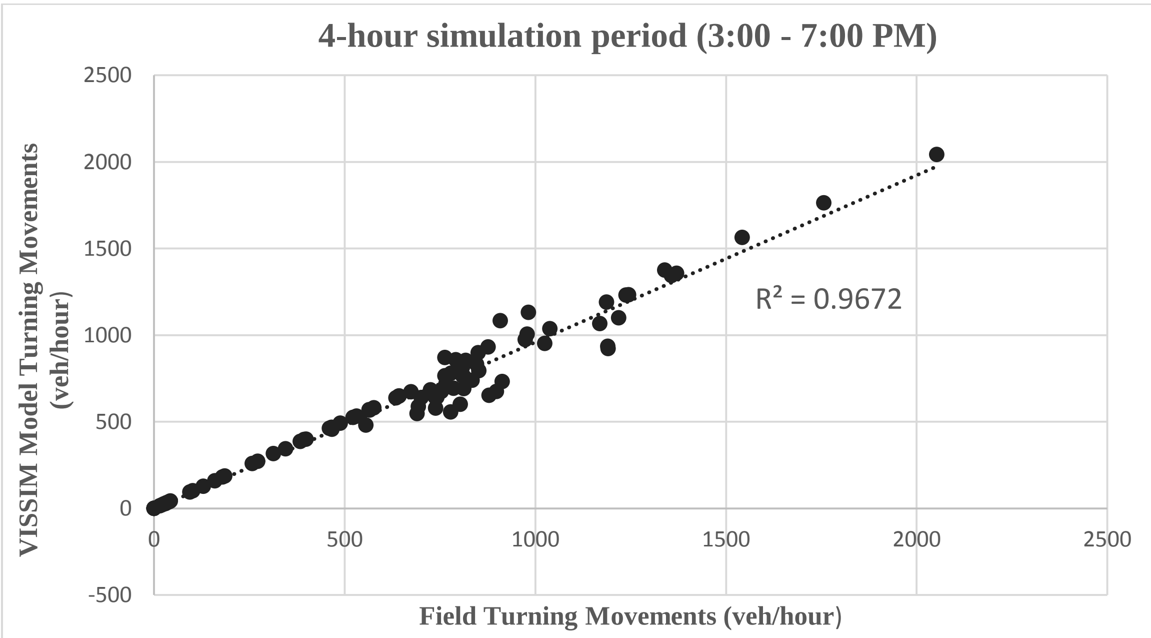

Figure 22: Turning movement counts, VISSIM versus field

Figure 22 compares the turning movement traffic volumes for the "No TSP" VISSIM model and the collected field data for the 4-hour period from 3:00PM – 7:00 PM. The (R^2) is approximately 0.967, showing that the model corresponds to the actual data very well. In addition to the turning movements, the George E. Havers (GEH) [**32**] empirical formula shown below was used as an acceptance criteria for the model. The GEH results for the model are shown in Figure 23; the GEH was <5.0 for 88% of the intersections, which meets the minimum criteria of GEH<5.0 for at least 75% of the intersections.

Modeled hourly flows compared with observed flows (Source: Wisconsin DOT Model Calibration Criteria) [32]	
GEH < 5.0	At least 75% of intersection turn volumes

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}}$$

** Where: **M** is the traffic volume from the traffic model (vehicle/hour) and
C is the real-world traffic count (vehicles/ hour).

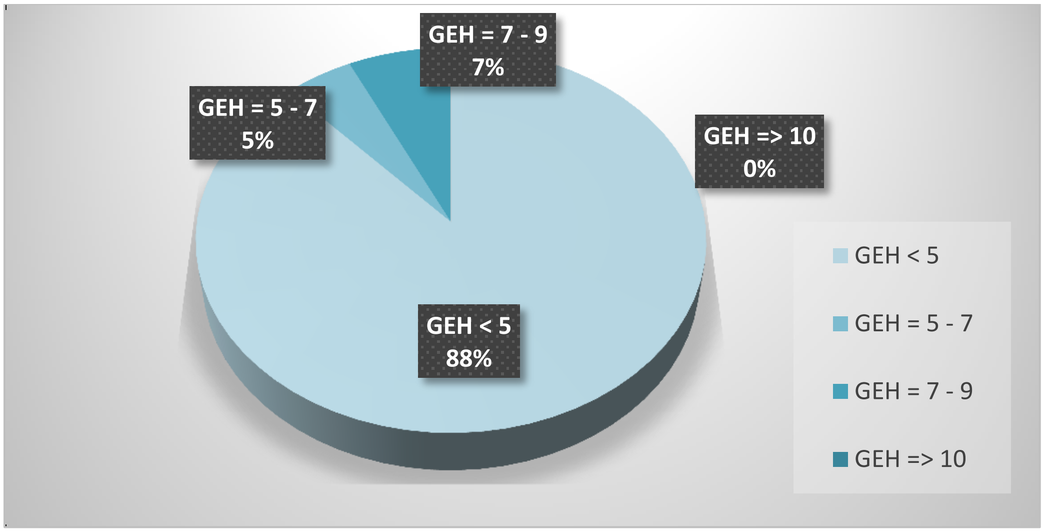

Figure 23: GEH results

The average speed profile along the corridor for each direction was also developed and compared between "No-TSP" VISSIM model (average of 57 model runs) and the average collected field data for the 4-hour period from 03:00 PM – 07:00 PM. The average speed profiles for the eastbound and westbound direction are shown in Figures 24 and 25, respectively. These figures show that the VISSIM model is accurate in modelling the vehicle speeds

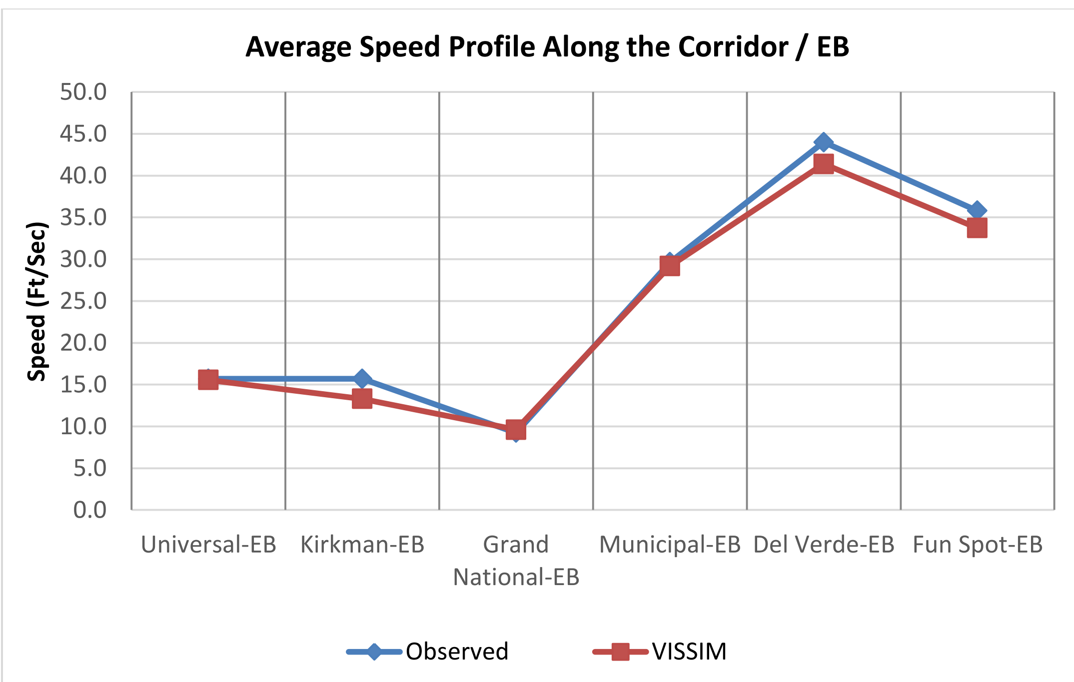

Figure 24: Average speed profile along the corridor (eastbound)

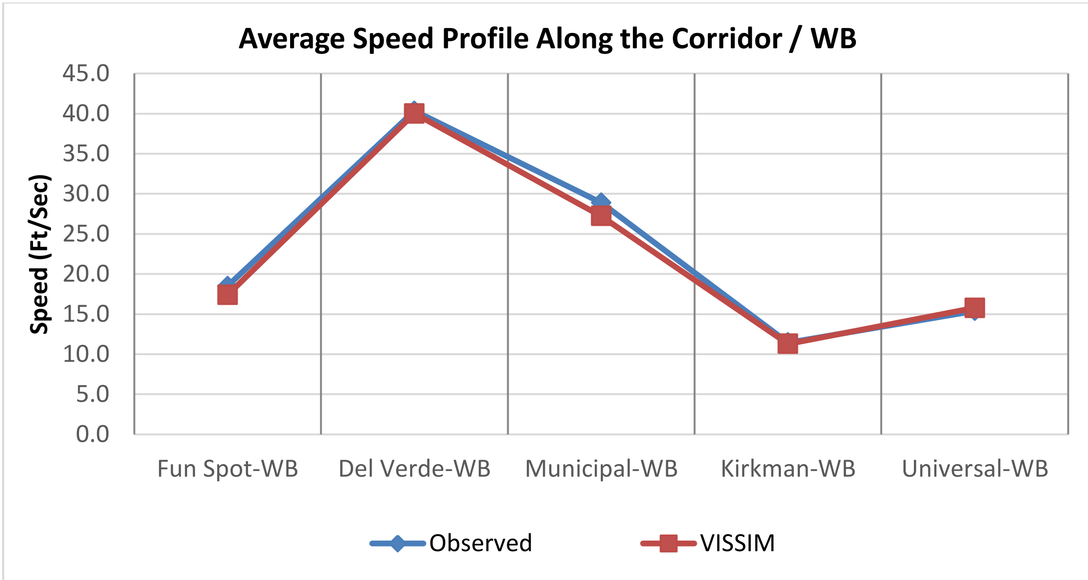

Figure 25: Average speed profile along the corridor (westbound)

The average travel times from the collected field data were used to validate the VISSIM model. Table 7 compares the average travel times between the "No TSP" VISSIM model (average of 57 model runs) and the average collected field data for the 4-hour period from 03:00 – 07:00 PM. These times show that the VISSIM model had lower times for the entire vehicular traffic, but higher times for the buses, with <7% discrepancies.

Table 7: Average travel times VISSIM vs. field

Travel time section		**VISSIM**	**Field**	**Difference**
		Travel time (sec)	Travel time (sec)	
1	All Veh – EB	391.4	404.3	-3.3%
2	All Veh - WB	378.2	403.7	-6.8%
3	Bus Only - EB	438.0	436	0.4%
4	Bus Only - WB	456.9	429	6.1%

11.3 VISSIM results

11.3.1 Average Speed

The VISSIM model results for average speed (ft/sec) is shown in Table 8. There was an increase in speed for all vehicles and for buses only compared to No TSP for all three TSP scenarios. The Unconditional TSP had the highest speeds of the four scenarios. However, the Unconditional TSP can create additional side street delay by having no restriction when TSP will be called (whether the TSP equipped bus is behind schedule or not). The Conditional TSP 3 minutes behind had higher average speeds than the Conditional TSP 5 minutes behind.

Table 8: Average speeds (feet/sec) in the corridor for all four scenarios

	No TSP	Unconditional	Conditional / 3 Minutes Behind	Conditional / 5 Minutes Behind
All vehicles / EB	15.9	**20.9**	18.7	17.5
All vehicles / WB	16.2	**19.1**	17.9	16.6
Bus Only / EB	4.6	**18.4**	17.8	16.9
Bus Only / WB	12.6	**14.7**	13.7	13.4

BOLD: Highest average speed (ft/sec) in each row
Underline: Lowest average speed (ft/sec) in each row

Figure 26 shows the average speed for all vehicles, including buses, at each signal for all four scenarios. Del Verde had the highest speeds in each direction under all four scenarios, with a maximum average speed of 41.9 ft/sec westbound under Conditional TSP 5 minutes behind. The reason for this is that the side street signal is rarely called during normal signal operations, resulting in the major street signal usually being green. The eastbound direction at Universal Boulevard had a maximum average speed of 21 ft/sec, whereas the westbound direction had a maximum average speed of 15.9 ft/sec. One reason for the lower westbound speeds is that traffic volumes increase approaching Universal Boulevard in the westbound direction, resulting in lower traffic speeds.

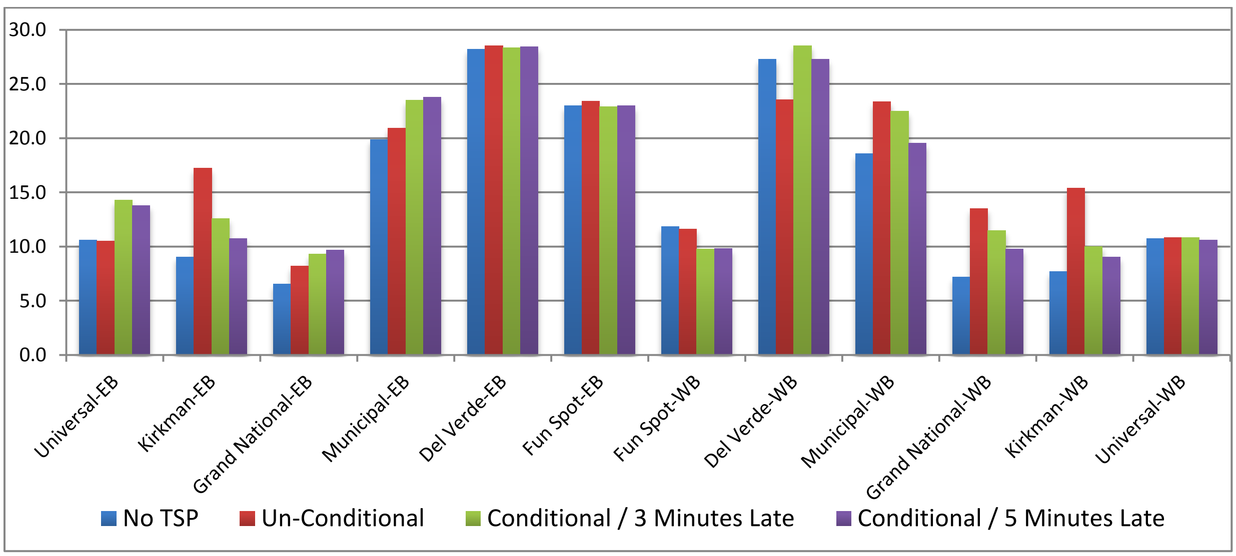

Figure 26: Average speeds (ft/sec) at signalized intersections

11.3.2 Average travel time

The average travel times through the corridor for No TSP, Unconditional TSP, Conditional TSP 3 minutes behind and Conditional TSP 5 minutes behind are shown in Table 9. The No TSP scenario had the highest travel times with 391.4 seconds for all vehicles eastbound, 378.2 seconds for all vehicles westbound, 438 seconds for buses eastbound and 486.9 seconds for buses westbound. As expected, the travel time for Unconditional TSP was lowest for both directions and for all vehicles, as well as for buses only. Additionally, Conditional 3 minutes behind had lower travel times than Conditional 5 minutes behind.

Table 9: Average travel time (in seconds) for all scenarios

Average Travel Time (seconds)	No TSP	Un-Conditional	Conditional / 3 Minutes Behind	Conditional / 5 Minutes Behind
All vehicles / EB	**391.4**	<u>297.5</u>	334.4	359.6
All vehicles / WB	**378.2**	<u>320.0</u>	342.1	360.3
Bus Only / EB	**438.0**	<u>339.8</u>	351.1	367.5
Bus Only / WB	**486.9**	<u>415.7</u>	450.6	460.9

BOLD: Highest travel time (seconds) in each row
Underline: Lowest travel time (seconds) in each row

11.3.3 Average total delay per vehicle

Table 10 shows the average total delay per vehicle in seconds for the corridor for both "all vehicles" and "buses only." The delays were largest for No TSP and smallest for Unconditional TSP. The Conditional TSP 3 minutes behind had lower total delay than the Conditional TSP 5 minutes behind. Even though Unconditional TSP had the lowest average total delay per vehicle for the vehicles traveling along the corridor, this scenario can cause increases in side street delays by the extension of the green or truncation of red on I-Drive. These increased delays can severely impact the side street traffic, especially at major intersections like Universal Boulevard or Kirkman Road.

Table 10: Average total delay per vehicle for all vehicles (in seconds) for all scenarios

Average total delay per vehicle for all vehicles	No TSP	Unconditional	Conditional / 3 Minutes Behind	Conditional / 5 Minutes Behind
All vehicles / EB	**166.3**	<u>71.9</u>	144.4	144.8
All vehicles / WB	**152.9**	<u>87.7</u>	140.2	154.0
Bus Only / EB	**192.6**	<u>74.8</u>	146.1	171.6
Bus Only / WB	**174.6**	<u>103.2</u>	165.0	172.4

BOLD: Highest total delay (seconds) in each row
Underline: Lowest total delay (seconds) in each row

11.3.4 Average number of stops per vehicle

The average number of stops in a network can indicate the level of traffic smoothness (Lin, et al, 2014) [**33**]. In theory, fewer vehicles stopping will represent a smoother traffic flow with less risk of vehicle-to-vehicle crashes. Table 11 shows the average total number of stops per vehicle on the corridor for both "all vehicles" and "buses only." The highest number of stops per vehicle occurred in the No TSP scenario for both all vehicles and buses only. Unconditional TSP had the lowest number of stops per vehicle for both all vehicles and buses only. Conditional TSP 3 minutes behind had less stops than Conditional TSP 5 minutes behind. Even though Unconditional TSP reduces the number of stops on I-Drive, it will increase the number of stops on the side streets since the signal will be called every time a bus approaches, whether or not that bus is behind schedule.

Table 11: Average number of stops for all vehicles for all scenarios

Average number of stops for all vehicles	No TSP	Unconditional	Conditional / 3 Minutes Behind	Conditional / 5 Minutes Behind
All vehicles / EB	**3.7**	<u>2.4</u>	3.4	3.5
All vehicles / WB	**3.4**	<u>2.8</u>	3.1	3.4
Bus Only / EB	**3.8**	<u>2.3</u>	3.0	3.4
Bus Only / WB	**3.5**	<u>2.5</u>	3.4	3.6

BOLD: Highest number of stops in each row
Underline: Lowest number of stops in each row

11.3.5 Average queue length

Tables 12 (eastbound) and 13 (westbound) show the average queue length in feet (ft) for the six signalized intersections along the TSP corridor. In the eastbound direction, the longest queues occurred at Kirkman for all four TSP scenarios and the shortest queues occurred at Del Verde for all four TSP scenarios. No TSP had the longest queue length at four intersections, Unconditional TSP had the longest queue length at two intersections, and Conditional TSP 3 minutes behind had the longest queue length at one intersection. Unconditional TSP had the shortest queue length at two intersections, Conditional TSP 3 minutes behind had the shortest queue length at one intersection, and Conditional TSP 5 minutes behind had the shortest queue length at three intersections. At Universal, Del Verde, and Fun Spot, all four scenarios had similar queue lengths.

Table 12: Average queue length for all scenarios (eastbound)

Eastbound average queue length (ft)	Universal	Kirkman	Grand National	Municipal	Del Verde	Fun Spot
No TSP	**34.0**	**173.3**	49.0	**8.3**	**0.5**	4.8
Unconditional	**34.0**	<u>77.2</u>	<u>23.7</u>	**8.3**	0.3	**5.2**
Conditional 3 Min	31.3	110.8	**54.5**	6.0	<u>0.0</u>	4.8
Conditional 5 Min	<u>30.3</u>	133.4	45.9	<u>5.6</u>	0.2	<u>4.6</u>

BOLD: Highest average queue length (feet) at each intersection
Underline: Lowest average queue length (feet) at each intersection

In the westbound direction, the longest queues occurred at Grand National for all four TSP scenarios and the shortest queues occurred at Del Verde for all four TSP scenarios. No TSP had the longest queue length at three intersections, Unconditional TSP had the longest queue length at one intersection, Conditional TSP 3 minutes behind had the longest queue length at one intersection, and Conditional TSP 5 minutes behind had the longest queue length at three intersections. No TSP had the shortest queue length at 2 intersections and Unconditional TSP had the shortest queue length at four intersections. At Universal and Del Verde, all four scenarios had similar queue lengths.

Table 13: Average Queue Length for all scenarios (westbound)

Westbound average queue length (ft)	Universal	Kirkman	Grand National	Municipal	Del Verde	Fun Spot
No TSP	40.3	**80.3**	87.5	**12.9**	**1.6**	18.5
Unconditional	**41.3**	26.1	41.1	7.6	1.2	20.7
Conditional 3 Min	41.0	73.5	94.3	8.8	1.3	**21.3**
Conditional 5 Min	**41.3**	78.6	**99.9**	10.5	**1.6**	20.3

BOLD: Highest average queue length (feet) at each intersection
Underline: Lowest average queue length (feet) at each intersection

11.3.6 Maximum queue length

Tables 14 (eastbound) and 15 (westbound) show the maximum queue length in feet (ft) for the six signalized intersections along the TSP corridor. In the eastbound direction, the largest maximum queue lengths occurred at Kirkman for No TSP, Conditional TSP 3 minutes behind, and Conditional TSP 5 minutes behind and at Universal for Unconditional TSP. The smallest maximum queue lengths occurred at Del Verde for all four TSP scenarios. No TSP had the largest maximum queue length at four intersections and Conditional TSP 3 minutes behind had the largest maximum queue length at two intersections. Unconditional TSP had the smallest maximum queue length at four intersections, Conditional TSP 3 minutes behind had the smallest maximum queue length at one intersection, and Conditional TSP 5 minutes behind had the smallest maximum queue length at one intersection.

Table 14: Maximum queue length for all scenarios (eastbound)

Eastbound maximum queue length (ft)	Universal	Kirkman	Grand National	Municipal	Del Verde	Fun Spot
No TSP	**278.3**	**523.0**	**256.5**	**142.3**	60.5	134.5
Unconditional	269.6	219.5	153.6	113.6	58.8	119.1
Conditional 3 Min	211.5	355.3	253.0	135.0	**66.5**	**137.0**
Conditional 5 Min	245.1	424.9	229.9	120.8	56.3	124.9

BOLD: Highest maximum queue length (feet) at each intersection
Underline: Lowest maximum queue length (feet) at each intersection

In the westbound direction, the largest maximum queue lengths occurred at Grand National for all four TSP scenarios. The smallest maximum queue lengths occurred at Del Verde for No TSP, Conditional TSP 3 minutes behind, and Conditional TSP 5 minutes behind and at Municipal for Unconditional TSP. No TSP had the largest maximum queue length at three intersections, Unconditional TSP had the largest maximum queue length at one intersection, and Conditional TSP 3 minutes behind had the largest maximum queue length at two intersections. No TSP had the smallest maximum queue length at one intersection, Unconditional TSP had the smallest maximum queue length at four intersections, and Conditional TSP 3 minutes behind had the smallest maximum queue length at one intersection.

Table 15: Maximum queue length for all scenarios (westbound)

Westbound maximum queue length (ft)	Universal	Kirkman	Grand National	Municipal	Del Verde	Fun Spot
No TSP	**239.3**	**222.5**	365.3	**144.8**	114.1	215.5
Unconditional	214.8	122.1	235.9	113.7	**128.0**	215.8
Conditional 3 Min	253.5	190.5	**381.8**	127.8	107.5	**265.8**
Conditional 5 Min	238.0	212.4	367.2	128.0	110.0	235.7

BOLD: Highest maximum queue length (feet) at each intersection
Underline: Lowest maximum queue length (feet) at each intersection

11.3.7 Crossing street average delay per vehicle

A concern of traffic engineers throughout the US is the effect of TSP on the operations of the crossing side streets at intersections where TSP is activated and either extends the green or truncates the red for the major street. The side streets at the six signalized intersections in the test corridor were analyzed in VISSIM to determine the amount of side street delay per vehicle; these results are shown in Table 16 for the four TSP scenarios.

Excessive side street delays occurred at Grand National NB and Kirkman NB and SB for Unconditional TSP, with delays of over 200 seconds. Municipal SB and Del Verde EB had very low delays (less than 10 seconds) for all four scenarios. Unconditional TSP had the highest side street delay for eight roads and Conditional TSP 3 minutes behind had the highest side street delay for three roads. No TSP had the lowest side street delay for two roads, Unconditional TSP had the lowest side street delay for one road, Conditional TSP 3 minutes behind had the lowest side street delay for seven roads, and Conditional TSP 5 minutes behind had the lowest side street delay for one road.

Figure 27 shows the information from the table in graphical format. This figure clearly shows that the average delay is much higher on Kirkman and Grand National for the Unconditional TSP compared to the other three scenarios. This model shows that conditional TSP (either 3 or 5 minutes behind schedule) does not cause a significant increase in side street delay. However, unconditional TSP can cause significant side street delay, especially for streets with large volumes, such as Kirkman Road.

Table 16: Crossing street average delay per vehicle (seconds) for all scenarios

Average delay (Sec)	NO-TSP	TSP-Unconditional	TSP-Cond-3-Min	TSP-Cond-5-Min
1. Universal NB	27.14	26.70	**28.53**	26.96
2. Universal SB	19.30	19.59	**21.86**	18.95
3. Kirkman NB	42.41	**215.93**	31.67	39.03
4. Kirkman SB	41.37	**258.59**	37.78	38.23
5. Grand NB	88.79	**280.18**	130.15	90.66
6. Grand SB	31.59	**65.35**	26.90	31.57
7. Municipal NB	13.71	**16.73**	10.77	12.00
8. Municipal SB	1.20	**1.33**	0.86	1.13
9. Del-Verde EB	6.25	**7.12**	5.34	6.33
10. Fun Spot EB	16.64	17.71	**19.59**	16.84
11. Fun Spot WB	15.01	**15.56**	13.70	15.15

BOLD: Highest cross street average delay (seconds) at each intersection
Underline: Lowest cross street average delay (seconds) at each intersection

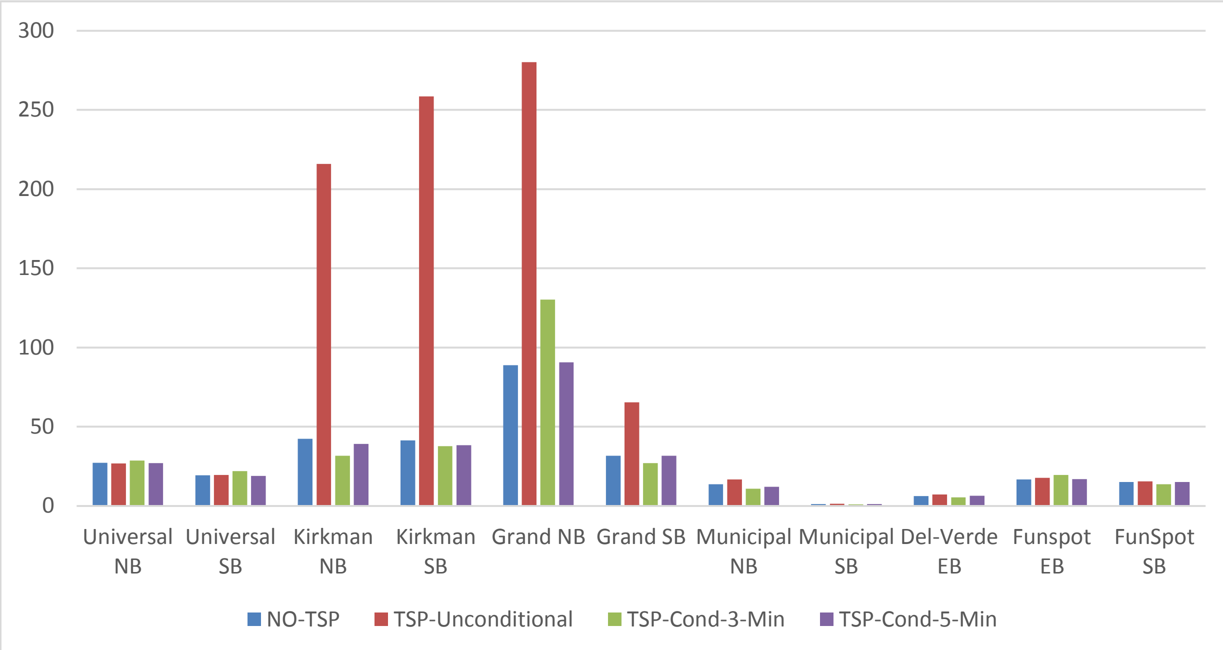

Figure 27: Crossing streets average delay per vehicle in seconds

11.4 Summary of VISSIM simulation results

Since it was difficult to have a fully controlled TSP experiment in the transportation corridor studied, VISSIM modeling was performed to provide a better analysis of TSP operations in the corridor. The No TSP, Unconditional TSP, and Conditional TSP scenarios were analyzed in the VISSIM model, with two Conditional TSP scenarios (3 minutes behind and 5 minutes behind). The 3 minute behind was the scenario used in the field, and the 5 minutes behind scenario was included in simulation as this is the industry standard (Kloos, 2002) [**24**]. The VISSIM model was used to analyze the average speed, average travel time, average total delay per vehicle, average number of stops per vehicle, average queue length, maximum queue length, and crossing street average delay per vehicle for all four TSP scenarios.

Average speeds were highest for Unconditional TSP and lowest for No TSP. Unconditional TSP had the lowest travel time for both directions and for all vehicles, with No TSP having the highest. The average total delay per vehicle was lowest for Unconditional TSP and highest for No TSP. Unconditional TSP also had the lowest average number of vehicle stops, whereas No TSP had the highest. In most cases, Unconditional TSP had lower average and maximum queue lengths compared to the other three scenarios and No TSP had higher average and maximum queue lengths. However, Unconditional TSP caused significant increases in side street delays, especially at Kirkman and Grand National, compared to no TSP. This makes the Unconditional TSP undesirable in real world applications. Both Conditional TSP scenarios improved on the No TSP scenario for the corridor parameters without significantly increasing the side street delays. Conditional TSP 3 minutes behind showed more improvements than Conditional TSP 5 minutes behind, with little difference in side street delay, showing that Conditional TSP 3 minutes behind is a good choice for this corridor.

12. Route Bus Passenger Savings

Travel time savings were calculated using both VISSIM model travel times and the average passenger load on the route. Route travel time reduction per run for each scenario (compared with No TSP as a control case or base case) was multiplied by the average passenger load on the route. Bus travel time savings were found by comparing the No TSP base case with Unconditional TSP, Conditional TSP 3 minutes behind, and Conditional TSP 5 minutes behind. Figures 28 and 29 and Table 17 show these calculated travel time savings for all TSP scenarios. Unconditional TSP showed the greatest savings for both eastbound and westbound (3240.6 passenger-seconds for eastbound and 925.6 passenger-seconds for westbound; however, as previously noted, the use of Unconditional TSP is detrimental to side street traffic. Conditional TSP 3 minutes behind showed better passenger travel time savings than Conditional TSP 5 minutes behind (3,042 passenger-seconds compared to 2,468 passenger-seconds for eastbound and 617 passenger-seconds compared to 442 passenger-seconds for westbound).

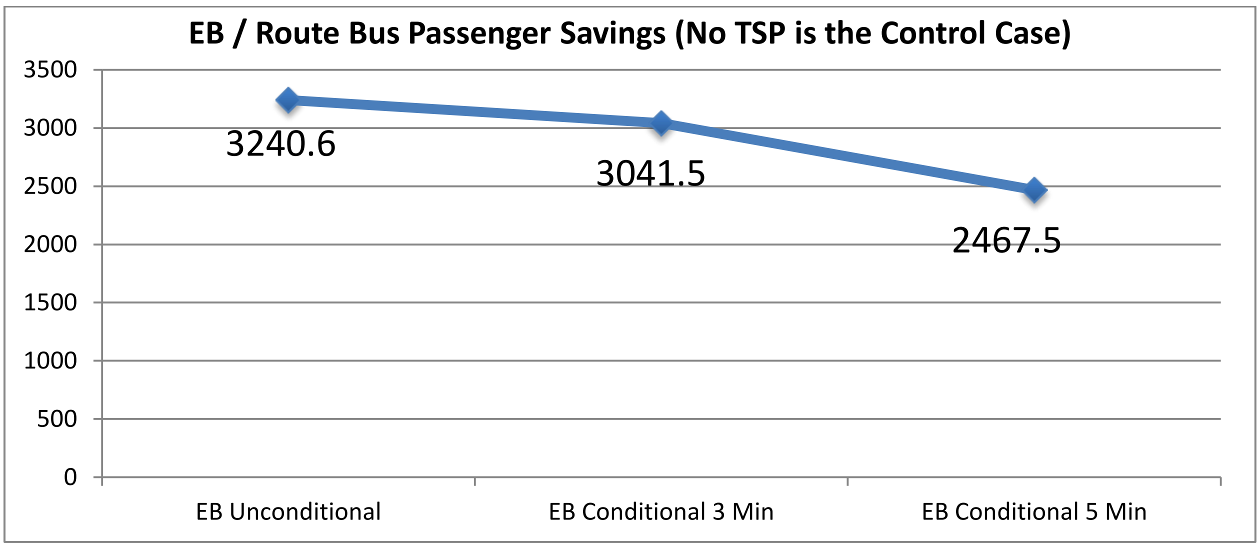

Figure 28: Eastbound route bus passenger savings

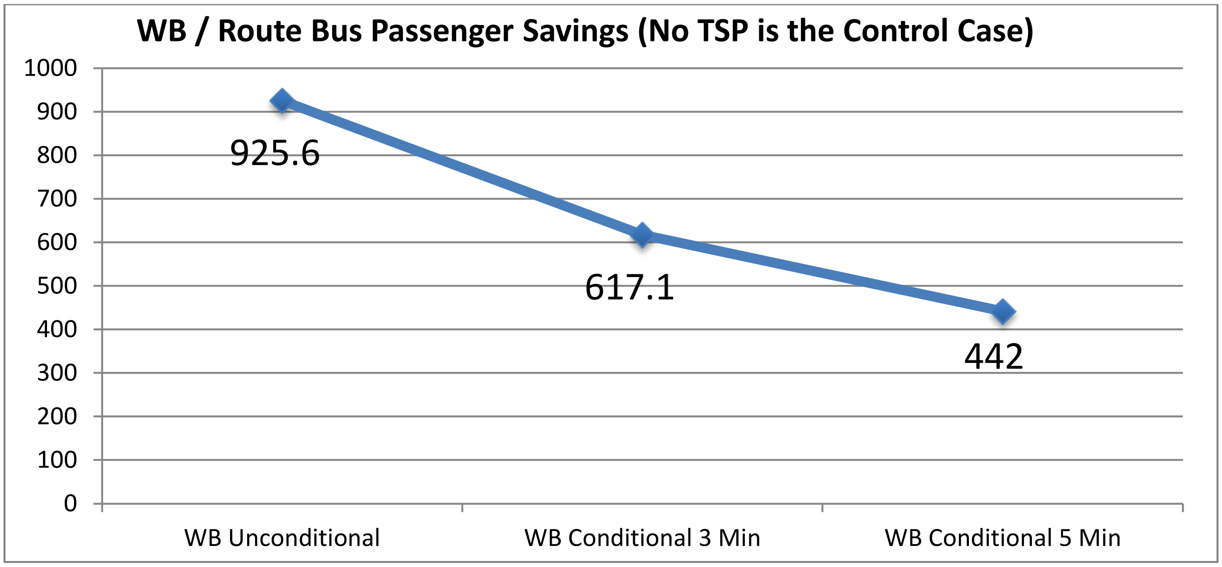

Figure 29: Westbound route bus passenger savings

Table 17: Route bus passenger savings (seconds)

VISSIM		Average Travel Time (seconds)	TT Reduction in seconds (No TSP Control Case)	Average Passenger Load on the Route	Route Bus Passenger Savings = TT Reduction * Average Passenger Load (passenger-seconds)
EB No TSP	-	438	-	35	-
EB Unconditional	-	339.8	98.2	33	3240.6
EB Conditional	3 min	351.1	86.9	35	3041.5
	5 min	367.5	70.5	35	2467.5
WB No TSP	-	486.9	-	17	-
WB Unconditional	-	415.7	71.2	13	925.6
WB Conditional	3 min	450.6	36.3	17	617.1
	5 min	460.9	26	17	442

13. Signal-by-Signal Passenger Savings

This analysis evaluated savings at each signal. Each signal delay reduction for each scenario (Unconditional TSP and Conditional TSP 3 minutes behind compared with No TSP as a control case) was multiplied by the actual number of passengers on the bus at the particular signal.

Table 18 shows the number of passengers, signal delay and its reduction compared with no TSP, and the signal-by-signal passenger savings. It can be seen that in the eastbound direction, Kirkman road had the highest saving for both TSP Unconditional (2304 passenger-seconds) and TSP Conditional 3 minutes behind (1049 passenger-seconds). Also, the same result is observed in the westbound direction, where Kirkman road had the highest saving for both TSP Unconditional (523 passenger-seconds) and TSP Conditional 3 min behind (158 passenger-seconds). There are usually larger savings for Unconditional TSP compared to Conditional TSP; however, Conditional TSP still experienced savings compared to No TSP.

Note that when we compare No TSP, TSP Unconditional, and TSP 3 minutes behind there were counter intuitive results where No TSP is better. It can be seen that some signals had a negative value like Grand National in eastbound direction (-191 passenger-seconds delay reduction) for TSP Conditional 3 minutes behind. One positive result is the delay reduction at Del Verde which has the most TSP calls. On the other hand, Kirkman had the highest savings for both directions.

Table 18: Signal by signal passenger savings

EB	No TSP		Un-Conditional				Conditional / 3 Minutes Late			
	Delay (Sec)	Avg. Passenger Load	Delay (Sec)	Delay Reduction from (No TSP)	Avg. Passenger Load	Savings = Delay Reduction (Sec) *Passenger Load	Delay (Sec)	Delay Reduction from (No TSP)	Avg. Passenger Load	Savings = Delay Reduction (Sec) *Passenger Load
Universal	19.62	33	19.59	0.03	32	0.96	19.7	-0.08	31	-2.48
Kirkman	93.48	34	19.17	74.31	31	2303.61	61.7	31.78	33	1048.74
Grand	23.8	35	9.81	13.99	31	433.69	29.6	-5.8	33	-191.4
Municipal	11.64	37	10.19	1.45	33	47.85	9.8	1.84	36	66.24
Del Verde	1.34	37	1.2	0.14	34	4.76	1.3	0.04	37	1.48
Fun Spot	6.76	37	6.4	0.36	34	12.24	6.8	-0.04	37	-1.48

WB	No TSP		Un-Conditional				Conditional / 3 Minutes Late			
	Delay (Sec)	Avg. Passenger Load	Delay (Sec)	Delay Reduction from (No TSP)	Avg. Passenger Load	Savings = Delay Reduction (Sec) *Passenger Load	Delay (Sec)	Delay Reduction from (No TSP)	Avg. Passenger Load	Savings = Delay Reduction (Sec) *Passenger Load
Universal	23.37	18	23.06	0.31	13	4.03	22.5	0.87	17	14.79
Kirkman	53.09	18	12.83	40.26	13	523.38	43.8	9.29	17	157.93
Grand	34.79	18	23.1	11.69	13	151.97	45.8	-11.01	17	-187.17
Municipal	8.79	17	13.51	-4.72	13	-61.36	7.4	1.39	16	22.24
Del Verde	4.46	17	9.33	-4.87	13	-63.31	2.9	1.56	16	24.96
Fun Spot	9.05	17	9.96	-0.91	13	-11.83	9.2	-0.15	16	-2.4

14. Vehicle Emissions

14.1 Emissions modeling

Due to increasing concerns about the global climate change, reduction of greenhouse emissions has gained tremendous attention worldwide and in the United States. The emitted carbon dioxide from the transportation industry is believed to remain the main source of total greenhouse emissions in the United States. Over the past decade, the transportation industry has emitted Green House Gases (GHG) more than any other energy user industry (Kahn Ribeiro et al., 2007) [**34**]. The transportation industry is responsible for 29 percent of total United States emissions and approximately 8 percent of global greenhouse emissions (U.S. EPA, 2008)[**35**]. The United States transportation sector should be able to cut greenhouse emissions by 20-25% by 2015 and 45-50% by 2030 (Greene, 2006)[**36**]. Carbon Dioxide accounts for 95 percent of the transportation related GHG emissions (US Department of Trasnportation, 2010) [**37**]. In 2006, light duty vehicles, such as passenger cars and light duty trucks, were responsible for 59 percent of the transportation emissions. For this reason, understanding the environmental impacts of different traffic strategies is crucial for the decision makers to choose the best appropriate strategy in any traffic operation situation.

The environmental burdens of three different real world TSP scenarios were evaluated in this research; TSP system turned off (No TSP); TSP system turned on unconditionally (Unconditional TSP); and TSP system turned on only under certain conditions of bus behind schedule (Conditional TSP). In order to evaluate the microscopic traffic conditions, the traffic simulation software VISSIM was used to compare the impacts of different TSP scenarios on the traffic condition in the corridor. Additionally, the Argonne National Lab's new Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool was used to evaluate the life cycle environmental burden of the different TSP strategies. AFLEET uses Motor Vehicle Emission Simulator (MOVES) [**2**], an EPA based model, and certification data to determine vehicle emissions (AFLEET, 2013) [**3**].

There have been numerous studies that have utilized MOVES as an emissions modeling framework. The EPA published several documents describing how MOVES works and how MOVES differs from MOBILE6 in terms of capabilities, inputs, and preliminary results (Beardsley et al., 2009) [**38**]. Younglove et al. used this software as a framework that is capable of predicting emissions across various scales [**21**]. In their study, various issues associated with on-road emission measurements and modeling has been presented. Also they examined an example of on-road emissions dataset and the reduction in estimation error through the addition of a short aggressive driving test to the in-use data (Younglove et al., 2005) [**21**]. Cadle et al. mentioned that there are several modal emissions models. However, probably the most significant efforts have been expended on the EPA's new emissions model, MOVES (Cadle et al., 2005) [**22**]. Huai et al. incorporated NH_3 data into a VSP/modal modeling framework [**23**]. Two modeling approaches were used in their study. First, second-by-second NH_3 emissions data were used to calculate NH_3 emission rates using a VSP binning methodology, as proposed for EPA's MOVES model. Finally, the NH_3 emissions module is applied to estimate the current NH_3 emission inventory in the South Coast air basin (SoCAB) and demonstrate the trend of NH_3

emissions inventories from the future mobile source fleet (Huai et al., 2005)[**23**]. Wang et al. used MOVES to estimate energy consumption for vehicles (Wang et al., 2008) [**24**].

14.2 Data collection for emissions modeling

Data from previous traffic studies along with some of the collected field data were used, including traffic volumes and vehicle classifications. Additionally, outputs from the developed VISSIM model were also required, including average delay and queue length. These data were collected for all the different TSP scenarios (No TSP, Unconditional TSP, and Conditional TSP). Collecting these data for all the different scenarios was critical for a before and after analysis to compare the environmental impacts of the different TSP scenarios.

14.3 AFLEET and environmental emissions

In this study, AFLEET was used to estimate the emissions of vehicles operating in the corridor. This new emission modeling system estimates emissions, including a broad range of pollutants, for mobile sources. AFLEET calculates the emissions of GHGs from on-road vehicles, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). This tool was recently released and yet to be used by the research community. It was developed for The Department of Energy's Clean City program and is able to estimate the petroleum use, GHG emissions, and cost of ownership of different alternative fuel technologies. Per the Argonne National Lab, this tool utilizes the background data and methodology of GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model (GREET, 2013) [**39**], as well as the EPA's Motor Vehicle Emission Simulator (MOVES)[**2**].

In order to calculate the associated emissions of different TSP scenarios, a similar methodology to Shipchandler et al. (2008) was used. Therefore, the amount of emissions for each scenario in the corridor was calculated using the following equation:

$$E = \sum_{i=1}^{m} \sum_{j=1}^{n} N_{ij} \times (Idle\ Time)_{ij} \times (Emissions\ Factor)_{ij}$$

Where;

E = Environmental Emissions, in mass units

i = the intersection index

j = the driving direction index

N = number of vehicles idling (taken from queue length tables)

Emission Factor = emissions per vehicle in the corridor, in mass/second (taken from AFLEET)

Idle Time = we assume it is equivalent to the delay time, in seconds (taken from delay time tables)

14.4 VISSIM outputs used in emission models

A variety of data needed for the emission models was obtained from VISSIM outputs. These VISSIM outputs included average delay and queue lengths and are shown in Tables 19-22.

Table 19: Average total delay per vehicle (seconds) – eastbound

Intersections	TSP Scenarios			
	No TSP	Un-Conditional	Conditional / 3 Minutes Behind	Conditional / 5 Minutes Behind
Universal	19.62	19.59	19.70	19.14
Kirkman	93.48	19.17	61.70	74.43
Grand National	23.80	9.81	29.60	23.81
Municipal	11.64	10.19	9.80	9.36
Del Verde	1.34	1.20	1.30	1.20
Fun Spot	6.76	6.40	6.80	6.44

Table 20: Average total delay per vehicle (seconds) – westbound

Intersections	TSP Scenarios			
	No TSP	Un-Conditional	Conditional / 3 Minutes Behind	Conditional / 3 Minutes Behind
Universal	23.37	23.06	22.50	23.68
Kirkman	53.09	12.83	43.80	51.58
Grand National	34.79	23.10	45.80	43.34
Municipal	8.79	13.51	7.40	8.60
Del Verde	4.46	9.33	2.90	4.42
Fun Spot	9.05	9.96	9.20	9.40

Table 21: Average and maximum queue length (ft) – eastbound

Intersections	TSP Scenarios							
	No TSP		Un-Conditional		Conditional / 3 Minutes Behind		Conditional / 3 Minutes Behind	
	Average	Max	Average	Max	Average	Max	Average	Max
Universal	34	278.3	34	269.6	31.3	211.5	30.3	245.1
Kirkman	173.3	523	77.2	219.5	110.8	355.3	133.4	424.9
Grand National	49	256.5	23.7	153.6	54.5	253	45.9	229.9
Municipal	8.3	142.3	8.3	113.6	6	135	5.6	120.8
Del Verde	0.5	60.5	0.3	58.8	0	66.5	0.2	56.3
Fun Spot	4.8	134.5	5.2	119.1	4.8	137	4.6	124.9

Table 22: Average and maximum queue length (ft) – westbound

Intersections	TSP Scenarios							
	No TSP		Un-Conditional		Conditional / 3 Minutes Behind		Conditional / 3 Minutes Behind	
	Average	Max	Average	Max	Average	Max	Average	Max
Universal	40.3	239.3	41.3	214.8	41	253.5	41.3	238
Kirkman	80.3	222.5	26.1	122.1	73.5	190.5	78.6	212.4
Grand National	87.5	365.3	41.1	235.9	94.3	381.8	99.9	367.2
Municipal	12.9	144.8	7.6	113.7	8.8	127.8	10.5	128
Del Verde	1.6	114.1	1.2	128	1.3	107.5	1.6	110
Fun Spot	18.5	215.5	20.7	215.8	21.3	265.8	20.3	235.7

14.5 Monte Carlo analysis

In addition to the standard emission modeling, a Monte Carlo simulation was used to account for the variability of critical input variables [**40**]. The use of a Monte Carlo simulation allowed for the estimation of the impact of the variability of input variables on the emissions of different TSP strategies. In the Monte Carlo Simulation method, the output can be estimated with random input variables. Applying a Monte Carlo Simulation method allowed for exploration of alternative cases and the finding of results in a set of strategies being selected with different probabilities.

In this research, variability arose from the idling time involved in each TSP scenario. For the purpose of this study, the idling time was considered to be equivalent to the delay time. Therefore, the variability ranges were extracted from the delay data in Tables 19 and 20. It was assumed that the total delay at each intersection varied with a range of (-20%, +20%) from reported expected values. Also, it was assumed that the variable parameter is uniformly distributed between these upper and lower boundaries. For the queue length, since VISSIM reports the average and maximum values, it was assumed that the minimum queue length at each intersection was equal to zero (No queue). Then, a Kernel Density Estimation (KDE) was fitted into these three values. Also, it was assumed that the reported idling emissions from AFLEET were average values. Therefore, these values were set to vary with a range of (-10%, +10%) from these average amounts. MATLAB® programming software was used to estimate the KDE and code the Monte Carlo Simulation (MATLAB, 2012) [**40**]. The Monte Carlo Simulation was then run for 100,000 replications; the results are discussed in the next section.

14.6 Analysis results

The developed methodology was applied to the available data from the I-Drive Corridor in Orlando, Florida. The associated idling emissions for each scenario are presented in the following subsections.

14.6.1 Carbon Monoxide (CO)

Figure 30 shows the histogram of Carbon Monoxide (CO) emissions for each scenario during the idling phase. The X-axis shows the amount of emissions in grams and Y-axis demonstrates the frequency of each emission. Looking at the different scenarios, No TSP had the highest range of emissions among the TSP scenarios. No TSP also had a higher density of emissions below 10 grams compared to the other scenarios. The average amount of CO emissions in the corridor was 4.3 g for No TSP, 3.5 g for Conditional TSP 5 minutes behind, 3.1 g for Conditional TSP 3 minutes behind, and 1.2 g for Unconditional TSP. These results clearly indicate that moving towards an Unconditional TSP system reduces the CO emissions in the idling phase.

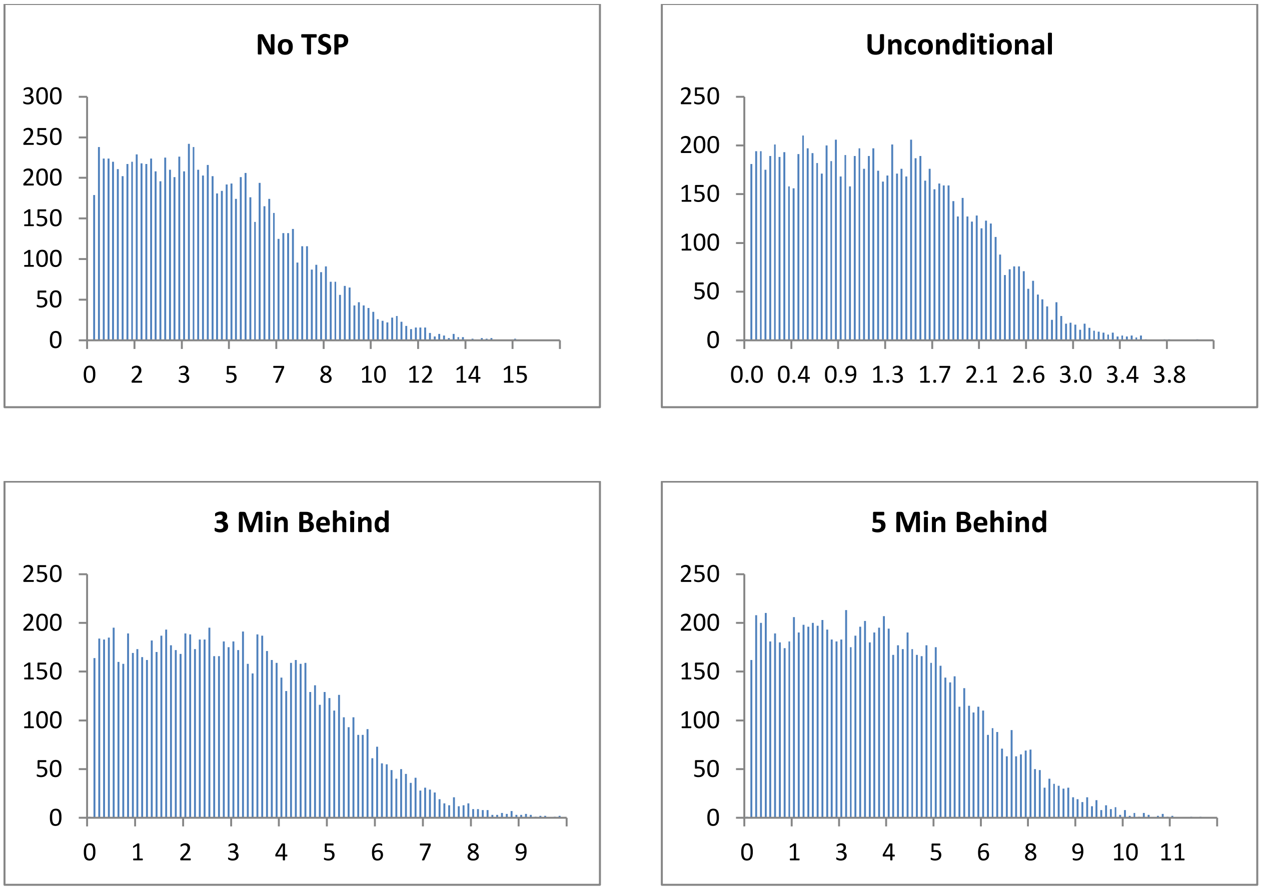

Figure 30 – Histogram of CO Emissions in idling phase for different TSP scenarios, in grams

14.6.2 Volatile Organic Compound (VOC)

Figure 31 shows the VOCs emitted during idling of vehicles in the studied corridor. It shows that the emitted VOCs in the Unconditional TSP is lower than in all of the other scenarios. The average amount of idling VOC emissions with this strategy is 80 mg. Conditional TSP 3 minutes behind had an average of 200 mg, Conditional TSP 5 minutes behind had an average of 230 mg, and No TSP had an average of 280 mg.

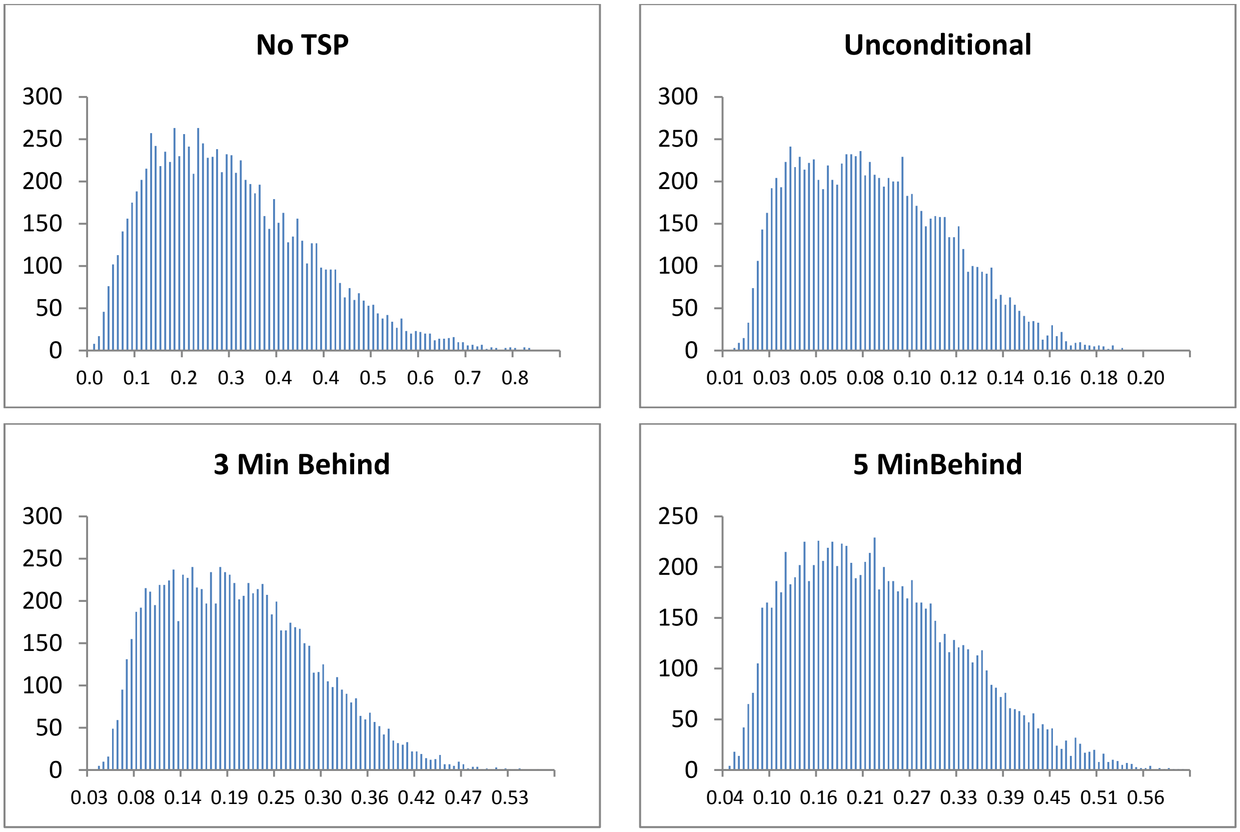

Figure 31 – Histogram of VOC emissions in idling phase for different TSP Scenarios, in grams

14.6.3 Nitrogen Oxide (NO_x)

The associated Nitrogen Oxide (NO_x) emissions in the idling phase for the different TSP scenarios are illustrated in Figure 32. The same trends described for CO and VOC emissions occurred for NO_x emissions. No TSP had the highest amount of NO_x emissions with an average of 520 mg, followed by Conditional TSP 5 minutes behind with an average of 420 mg, then Conditional TSP 3 minutes behind with an average of 370 mg, then Unconditional TSP with an average of 150 mg NO_x emissions.

14.6.4 Other emissions

Figure 33 shows other estimated emissions during the idling phase. The same trend found in the previous emissions was discovered for these types of emissions. However, the emissions of $PM_{2.5}$ and PM_{10} seem to be independent of the queue length as their related histogram distributions were likely to follow a normal-shaped distribution. In other words, the amounts of emission for these two types of air pollutants are too low that the effect of non-symmetric queue length distribution does not have a considerable effect on the overall emissions.

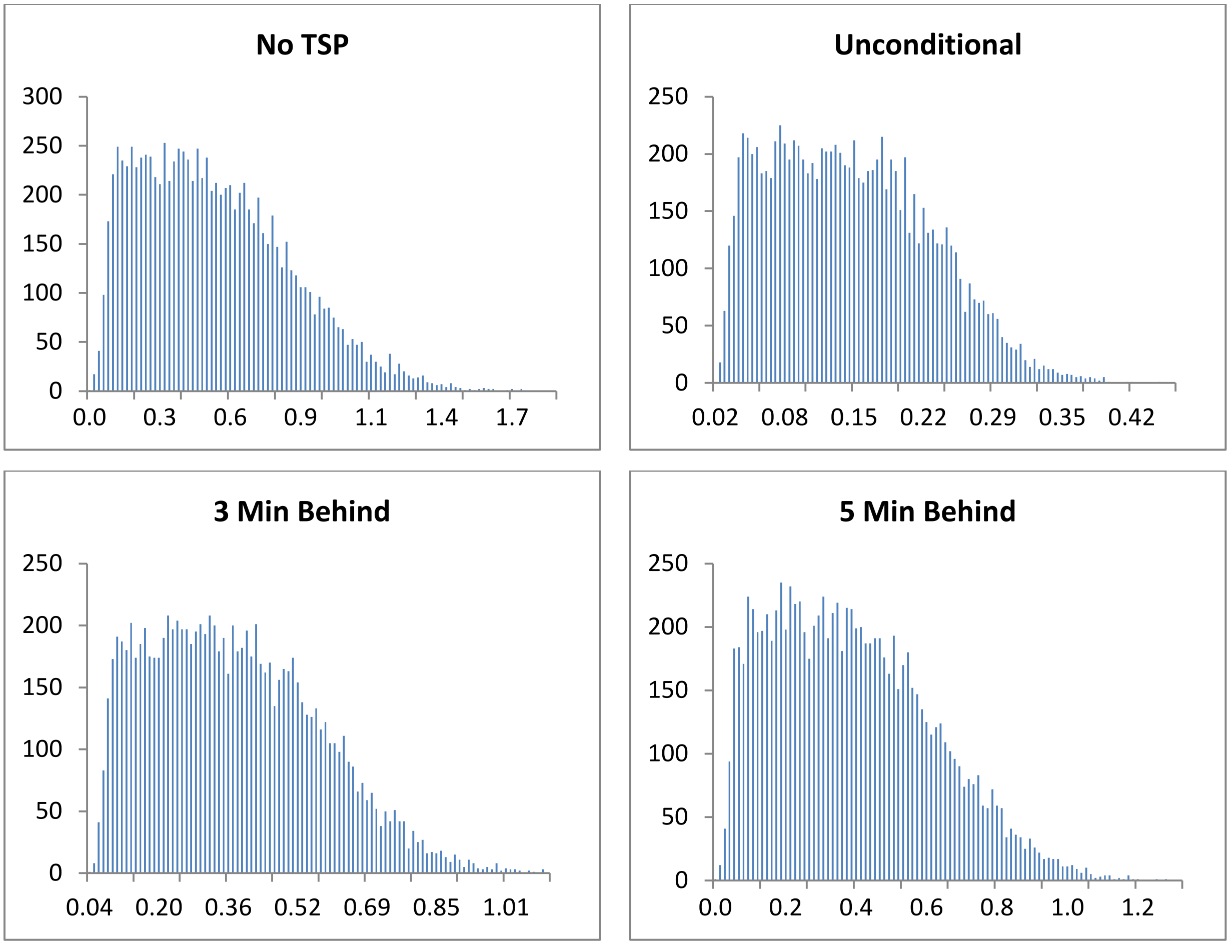

Figure 32: Histogram of NOx emissions in idling phase for different TSP scenarios, in grams

14.6.5 Comparison of eastbound and westbound emissions

During data collection, it was discovered that the queue lengths in the east and west bound were different lengths. Therefore, a comparison of eastbound and westbound emission was performed. As an example, Figure 34 shows the comparison between eastbound and westbound Carbon Monoxide (CO) emissions in grams. This figure shows that the amount of emissions in the eastbound direction was more than in the westbound direction, except for the Unconditional TSP scenario. This means that applying Unconditional TSP helps the traffic in the eastbound direction and decreases its associated CO emissions more than in the westbound direction, even though the emissions in the eastbound direction are more than in the westbound direction for the normal traffic condition.

Overall, the emissions analyses show that TSP is effective at reducing emissions, with Unconditional TSP providing the most benefit. However, since Unconditional TSP is not a practical choice in the real world, since it significantly increases side street delay and can cause buses to be ahead of schedule, it is important to look at the results for Conditional TSP. Conditional TSP 3 minutes behind decreases most emissions compared to No TSP and provides better reduction than Conditional TSP 5 minutes behind, showing that Conditional TPS 3 minutes behind is a beneficial TSP scenario.

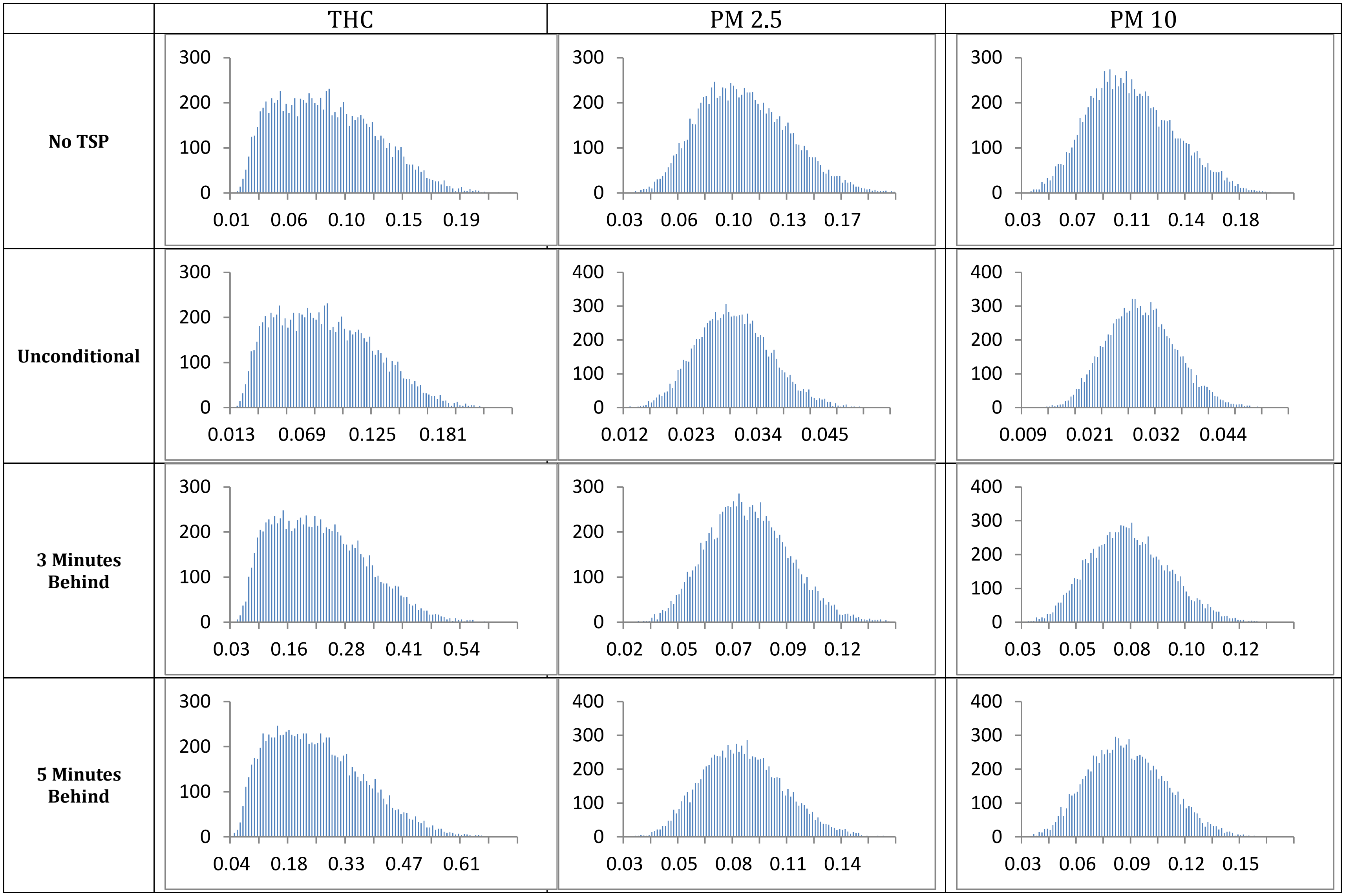

Figure 33: Histogram of THC, PM 2.5, and PM 10 Emissions in idling phase for different TSP Scenarios, in grams

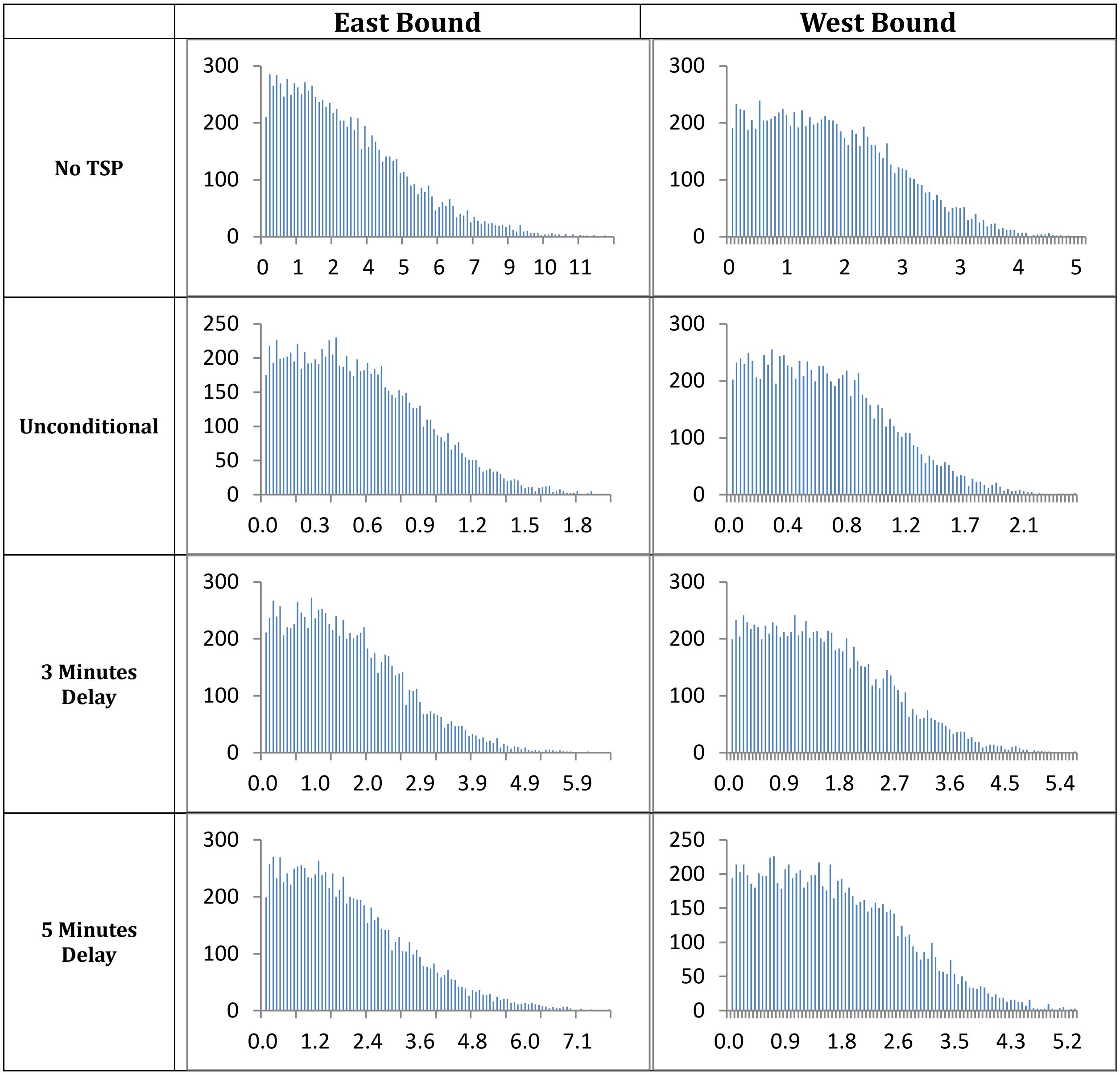

Figure 34: Comparison of CO emission histograms in for east and westbound in Idling phase for different TSP scenarios, in grams

15. Conclusion

Several methods were used to determine whether TSP was effective in reducing bus travel time along the test corridor and whether TSP can reduce the environmental impacts of the traffic along the corridor. Automatic passenger counts from LYNX were used to determine that the peak hour of passenger demand occurs between 4:00 PM and 5:00 PM on Monday through Friday; this was also verified in the field. This information was useful in considering any delays to the bus that were not signal related (e.g. increased volumes or delays caused by passenger boarding).

Data exploration with statistical analysis was initially used to evaluate three different TSP scenarios: No TSP, Unconditional TSP, and Conditional TSP 3 minutes behind. Additional analysis was also conducted using VISSIM [**1**]. The data collected in this research, along with data from the Kittleson study [**13**], was analyzed; both had limited data, but the analysis showed that Conditional TSP had some positive effect. One noticeable effect was that Conditional TSP improved bus schedule reliability and adherence. Improving bus schedule adherence might attract additional patrons to use the transit system, thereby reducing the amount of single occupant vehicles on the roadway. However, it was not possible to see the full benefits of Conditional TSP or evaluate Conditional TSP with different "behind schedule" time durations (i.e., 3 and 5 minutes). Therefore, a VISSIM simulation model was developed to better study TSP and see if it was effective.

The VISSIM model utilized in this research was used to determine average speeds, average travel times, average total delay per vehicle, average number of stops per vehicle, average queue lengths, maximum queue lengths, and average delay per vehicle on crossing street. Multiple VISSIM runs were performed for the following four TSP scenarios: No TSP, Unconditional TSP, Conditional TSP 3 minutes behind, and Conditional TSP 5 minutes behind. VISSIM results showed that TSP was effective in reducing travel times and delays for transit service. Unconditional TSP had the best improvements on I-Drive, but it had a significant negative impact on side street traffic. Therefore, it was concluded that Conditional TSP 3 minutes behind was the most effective TSP scenario, since it reduced travel times and delays for I-Drive more than Conditional TSP 5 minutes behind without significantly increasing side street delays. Conditional TSP also caused fewer vehicle stops than No TSP; this is desirable since fewer vehicles stopping will result in a smoother traffic flow and less risk of vehicle-to-vehicle crashes.

Analyzing signal by signal passenger delay found that in the eastbound direction, No TSP had the most delay at four of the six signals. In the westbound direction, No TSP showed the highest delay at three of the six signals. Unconditional TSP had the lowest delay at each signal in the eastbound direction. There was mixed results in the westbound direction. Overall route bus passenger savings and signal by signal passenger savings indicated that bus passengers benefited from Conditional TSP by increasing their travel time savings.

Vehicle emissions were also modeled using AFLEET **[3]** and a Monte Carlo simulation to estimate the environmental effects of implementing TSP along the I-Drive test corridor. Environmental burdens were evaluated for the four TSP scenarios studied. It was found that using TSP technology reduces the environmental emissions in the corridor. Unconditional TSP was the most effective at reducing emissions, then Conditional TSP 3 minutes behind, then

Conditional TSP 5 minutes behind. However, since Unconditional TSP is not practical due to the negative effects on side street delays and schedule adherence, Conditional TSP 3 minutes behind has the most environmental benefits. If the TSP system is used system-wide in the field, there will be a larger reduction of greenhouse gas emissions, due to the amount of buses affected (over 270).

Based on the research so far, it can be concluded that Transit Signal Priority is beneficial for transit operations in the studied I-Drive corridor. TSP ensures that buses behind schedule are granted signal priority; this contributes to a better adherence to the bus schedule and increases transit reliability. By reducing bus delay and decreasing travel time, TSP can lead to a more sustainable transportation system. There is no one solution to reduce the transportation industry's contribution to greenhouse gases and global warming, but TSP can be one component of a sustainable transportation system. TSP can make bus travel more attractive, leading to a potential decrease in individual vehicle usage and a corresponding improvement in the efficiency of the transit system by increasing ridership. It could also lead to a decrease in greenhouse gases and thus reduce the rate of temperature increases and sea level rise. TSP can be an effective strategy to reduce the environmental impacts of the transportation industry if it is used on a larger scale throughout the United States and the world.

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Appendix A

Sample of spreadsheet for Two -Factor ANOVA preparation for Eastbound red signal delay

** Where: Condition 1 if No TSP is equal to Unconditional then equal to 1: if not then equal to 0
Condition 2 if No TSP is equal to Conditional then equal to 1: if not then equal to 0

LOCATION (L)	SIGNAL TYPE (S)	CONDITION (C)	TIME DELAY (T)	Condition (1)	Condition (2)
Universal (EB)	TSP	NO TSP	15.0	0	0
Universal (EB)	TSP	NO TSP	19.0	0	0
Universal (EB)	TSP	NO TSP	21.0	0	0
Universal (EB)	TSP	NO TSP	22.4	0	0
Universal (EB)	TSP	NO TSP	23.0	0	0
Universal (EB)	TSP	NO TSP	26.0	0	0
Universal (EB)	TSP	NO TSP	31.0	0	0
Universal (EB)	TSP	NO TSP	35.7	0	0
Universal (EB)	TSP	NO TSP	36.0	0	0
Universal (EB)	TSP	NO TSP	41.0	0	0
Universal (EB)	TSP	NO TSP	41.0	0	0
Universal (EB)	TSP	NO TSP	41.0	0	0
Universal (EB)	TSP	NO TSP	102.0	0	0

Red signal delay eastbound

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Welcome to Minitab, press F1 for help.
Retrieving project from file: 'C:\Users\Frank\Documents\East and West Red
Signal and Passenger Delay Revised.MPJ'
```

Regression Analysis: Square Root D versus Condition (1, Condition (2, uni*cond1, ...

```
Method

Categorical predictor coding  (1, 0)

Continuous predictor standardization
Levels coded to -1 and +1
```

Predictor	Low	High
Condition (1)	0	1
Condition (2)	0	1
uni*cond1	0	1
uni*cond2	0	1
kirk*cond1	0	1
kirk*cond2	0	1
GrandN*cond1	0	1
GrandN*cond2	0	1
Municipal*cond1	0	1
Municipal*cond2	0	1
Delverde*cond1	0	1
Delverde*cond2	0	1
Funspot*cond1	0	1
Funspot*cond2	0	1

Stepwise Selection of Terms

α to enter = 0.05, α to remove = 0.05

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	1207.98	172.568	27.73	0.000
uni*cond2	1	27.45	27.453	4.41	0.036
kirk*cond2	1	25.80	25.804	4.15	0.043
LOCATION (L)	5	1142.44	228.488	36.72	0.000
Error	322	2003.76	6.223		
Lack-of-Fit	12	45.08	3.757	0.59	0.846
Pure Error	310	1958.67	6.318		
Total	329	3211.74			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.49456	37.61%	36.26%	34.23%

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2.478	0.546	4.54	0.000	
uni*cond2	0.811	0.386	2.10	0.036	1.28
kirk*cond2	-0.786	0.386	-2.04	0.043	1.28
LOCATION (L)					
Del Verde (EB)	-2.177	0.515	-4.23	0.000	1.95
Fun Spot (EB)	-1.087	0.515	-2.11	0.035	1.95
Grand National (EB)	2.291	0.515	4.45	0.000	1.95
Kirkman (EB)	2.865	0.551	5.20	0.000	2.24
Municipal (EB)	-1.891	0.515	-3.67	0.000	1.95

Regression Equation in Uncoded Units

LOCATION (L)

Del Verde (EB) Square RootDelay = 0.276 + 1.622 uni*cond2 - 1.572 kirk*cond2

Fun Spot (EB) Square RootDelay = 1.366 + 1.622 uni*cond2 - 1.572 kirk*cond2

Grand National (EB) Square RootDelay = 4.745 + 1.622 uni*cond2 - 1.572 kirk*cond2

```
Kirkman (EB)         Square RootDelay = 5.319 + 1.622 uni*cond2 - 1.572 kirk*cond2

Municipal (EB)       Square RootDelay = 0.562 + 1.622 uni*cond2 - 1.572 kirk*cond2

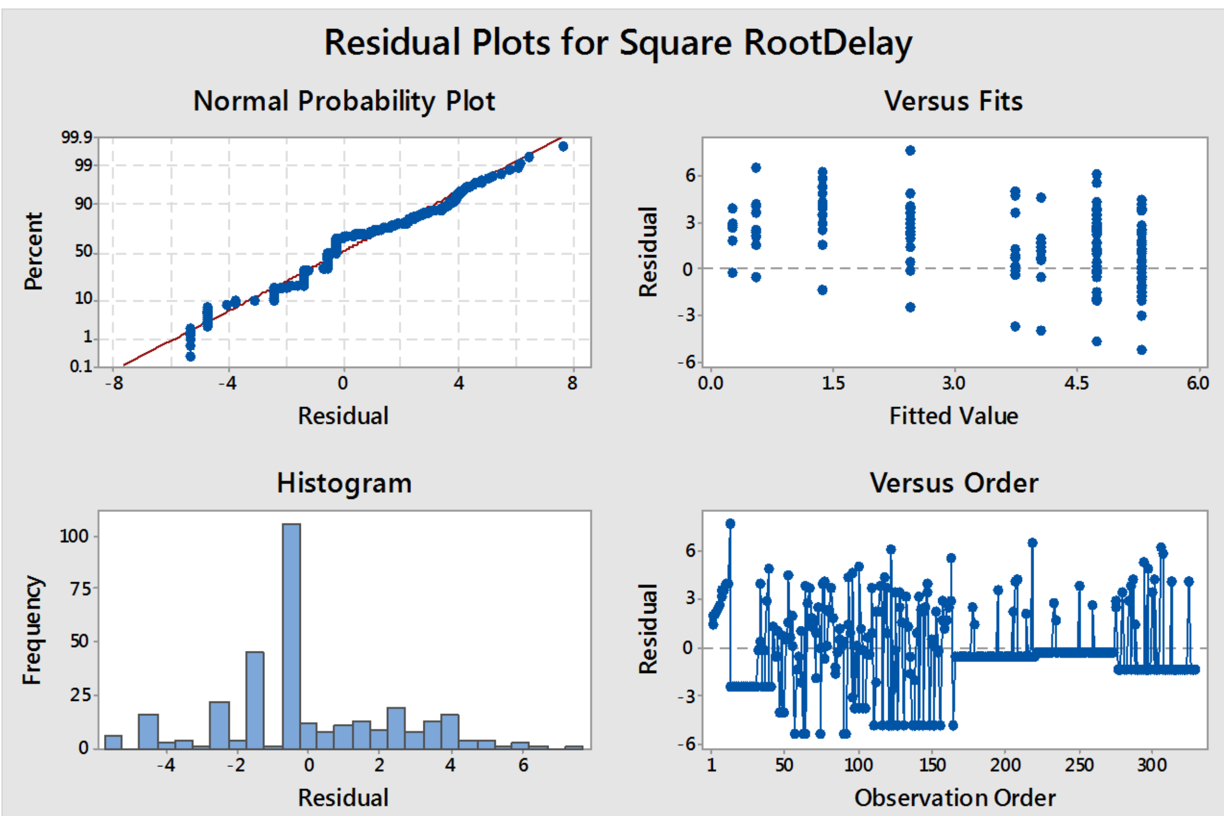
Universal (EB)       Square RootDelay = 2.453 + 1.622 uni*cond2 - 1.572 kirk*cond2


Fits and Diagnostics for Unusual Observations

        Square
Obs  RootDelay    Fit   Resid  Std Resid
 13     10.100  2.453   7.646       3.10  R
 57      0.000  5.319  -5.319      -2.16  R
 63      0.000  5.319  -5.319      -2.16  R
 65      0.000  5.319  -5.319      -2.16  R
 75      0.000  5.319  -5.319      -2.16  R
 91      0.000  5.319  -5.319      -2.16  R
 92      0.000  5.319  -5.319      -2.16  R
101      8.775  3.746   5.029       2.09  R
123     10.817  4.745   6.072       2.46  R
164     10.237  4.745   5.493       2.22  R
218      7.043  0.562   6.480       2.62  R
295      6.557  1.366   5.191       2.10  R
306      7.537  1.366   6.170       2.50  R
307      7.141  1.366   5.775       2.34  R

R  Large residual
```

Residual Plots for Square Root Delay



Red signal delay westbound

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Welcome to Minitab, press F1 for help.
Retrieving project from file: 'C:\Users\Frank\Documents\East and West Red
Signal and Passenger Delay Revised.MPJ'
```

Results for: Worksheet 2

Regression Analysis: Square Root versus Condition (1, Condition (2, uni*cond1, ...

```
Method

Categorical predictor coding  (1, 0)

Continuous predictor standardization
Levels coded to -1 and +1

Predictor         Low  High
Condition (1)       0     1
Condition (2)       0     1
uni*cond1           0     1
uni*cond2           0     1
kirk*cond1          0     1
kirk*cond2          0     1
GrandN*cond1        0     1
gradN*cond2         0     1
Municipal*cond1     0     1
Municipal*cond2     0     1
Del verde*cond1     0     1
Delverde*cond2      0     1
funspot*cond 1      0     1
funspot*cond2       0     1


Stepwise Selection of Terms

α to enter = 0.05, α to remove = 0.05


Analysis of Variance

Source            DF   Adj SS   Adj MS  F-Value  P-Value
Regression         8  1581.15  197.644    25.05    0.000
  uni*cond1        1    68.37   68.375     8.66    0.003
  gradN*cond2      1    35.68   35.678     4.52    0.034
  LOCATION (L)     6  1454.04  242.340    30.71    0.000
Error            327  2580.49    7.891
  Lack-of-Fit     23   233.29   10.143     1.31    0.156
  Pure Error     304  2347.20    7.721
Total            335  4161.65


Model Summary
```

S	R-sq	R-sq(adj)	R-sq(pred)
2.80917	37.99%	36.48%	*

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.459	0.756	0.61	0.544	
uni*cond1	-1.443	0.490	-2.94	0.003	1.18
gradN*cond2	0.922	0.433	2.13	0.034	1.28
LOCATION (L)					
Del Verde (WB)	-0.614	0.533	-1.15	0.251	1.68
Fun Spot (WB)	1.004	0.533	1.88	0.061	1.68
Grand National (WB)	3.266	0.576	5.67	0.000	1.96
Kirkman (WB)	4.192	0.533	7.86	0.000	1.68
Municipal (EB)	2.48	2.83	0.87	0.383	1.02
Universal (WB)	5.161	0.561	9.20	0.000	1.86

Regression Equation in Uncoded Units

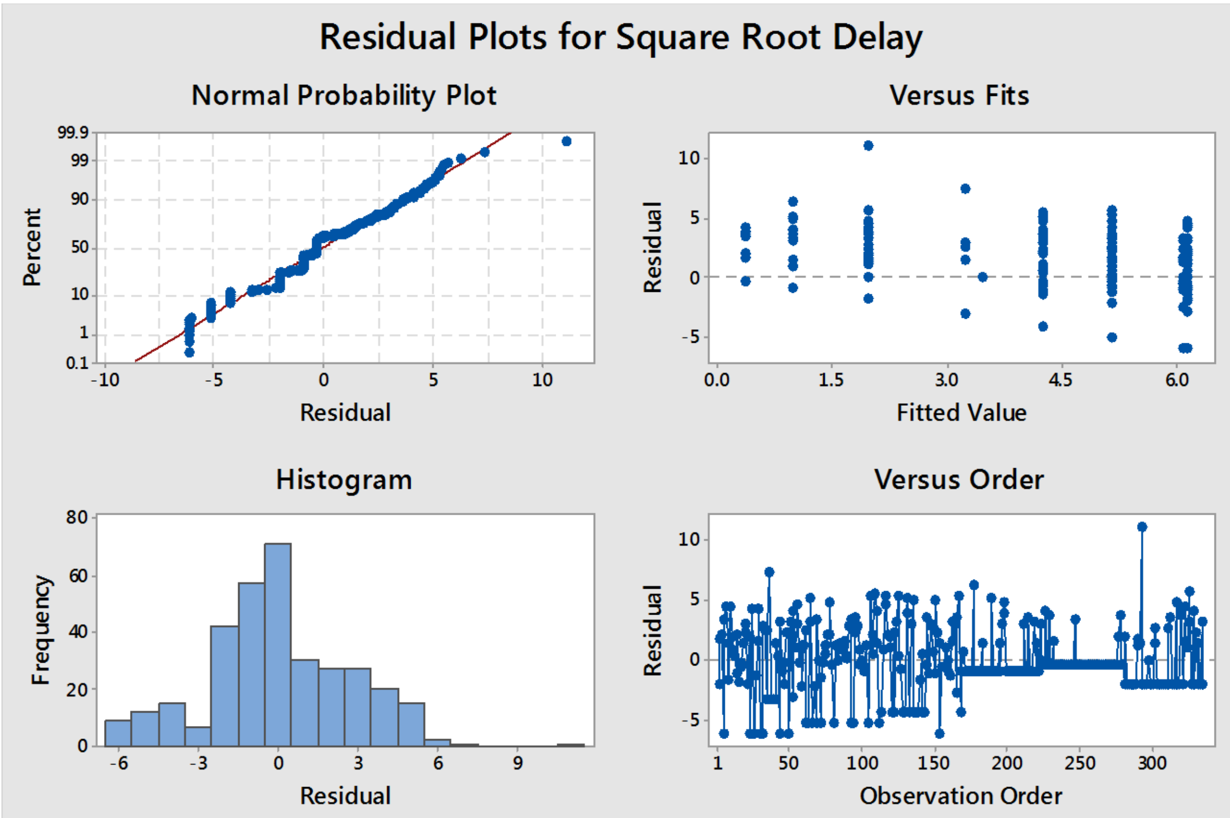
```
LOCATION (L)
Del Verde (WB)       Square Root Delay = 0.366 - 2.885 uni*cond1 + 1.843 gradN*cond2

Fun Spot (WB)        Square Root Delay = 1.984 - 2.885 uni*cond1 + 1.843 gradN*cond2

Grand National (WB)  Square Root Delay = 4.246 - 2.885 uni*cond1 + 1.843 gradN*cond2

Kirkman (WB)         Square Root Delay = 5.172 - 2.885 uni*cond1 + 1.843 gradN*cond2

Municipal (EB)       Square Root Delay = 3.46 - 2.885 uni*cond1 + 1.843 gradN*cond2

Municipal (WB)       Square Root Delay = 0.980 - 2.885 uni*cond1 + 1.843 gradN*cond2

Universal (WB)       Square Root Delay = 6.141 - 2.885 uni*cond1 + 1.843 gradN*cond2
```

Fits and Diagnostics for Unusual Observations

Obs	Square Root Delay	Fit	Resid	Std Resid		
4	0.00	6.14	-6.14	-2.21	R	
23	0.00	6.14	-6.14	-2.21	R	
25	0.00	6.14	-6.14	-2.21	R	
26	0.00	6.14	-6.14	-2.21	R	
30	0.00	6.14	-6.14	-2.21	R	
31	0.00	6.14	-6.14	-2.21	R	
32	6.08	3.26	2.83	1.06		X
33	5.66	3.26	2.40	0.90		X
34	0.00	3.26	-3.26	-1.22		X
35	5.66	3.26	2.40	0.90		X
36	10.58	3.26	7.33	2.75	R	X
37	0.00	3.26	-3.26	-1.22		X
38	0.00	3.26	-3.26	-1.22		X
39	0.00	3.26	-3.26	-1.22		X
40	0.00	3.26	-3.26	-1.22		X
41	4.58	3.26	1.33	0.50		X
43	0.00	6.14	-6.14	-2.21	R	
50	0.00	6.14	-6.14	-2.21	R	
154	0.00	6.09	-6.09	-2.25	R	
177	7.28	0.98	6.30	2.26	R	
224	3.46	3.46	0.00	*		X

```
293   13.08  1.98  11.09        3.98  R
326    7.62  1.98   5.63        2.02  R

R  Large residual
X  Unusual X
```

Residual Plots for Square Root Delay



<u>Passenger delay eastbound</u>

Results for: Worksheet 3

Regression Analysis: Square Root versus Condition (1, Condition (2, uni*cond1, ...

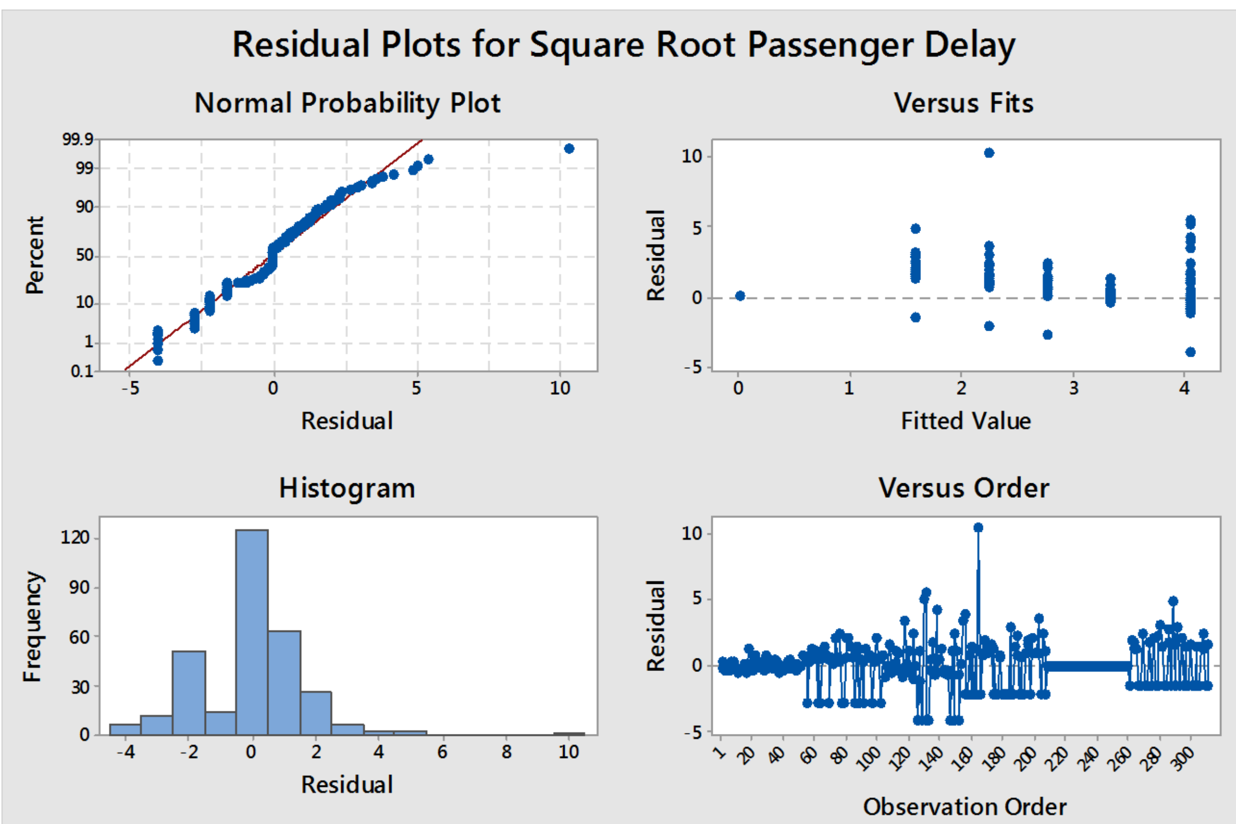
```
Method

Categorical predictor coding  (1, 0)

Continuous predictor standardization
Levels coded to -1 and +1

Predictor          Low  High
Condition (1)        0     1
Condition (2)        0     1
uni*cond1            0     1
```

```
uni*cond2           0     1
kirk*cond1          0     1
kirk*cond2          0     1
GrandN*cond1        0     1
gradN*cond2         0     1
Municipal*cond1     0     1
Municipal*cond2     0     1
Del verde*cond1     0     1
uni*cond1_1_1       0     1
funspot*cond 1_1    0     1
funspot*cond2       0     1


Stepwise Selection of Terms

α to enter = 0.05, α to remove = 0.05


Analysis of Variance

Source           DF   Adj SS   Adj MS  F-Value  P-Value
Regression        5   605.49  121.098    41.03    0.000
  LOCATION (L)    5   605.49  121.098    41.03    0.000
Error           307   906.05    2.951
  Lack-of-Fit    24    44.15    1.840     0.60    0.930
  Pure Error    283   861.90    3.046
Total           312  1511.54


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.71794  40.06%     39.08%      37.70%


Coded Coefficients

Term                     Coef  SE Coef  T-Value  P-Value   VIF
Constant                3.474    0.238    14.58    0.000
LOCATION (L)
  Del Verde (EB)       -3.189    0.337    -9.46    0.000  1.67
  Fun Spot (EB)        -2.216    0.337    -6.58    0.000  1.67
  Grand National (EB)   0.050    0.337     0.15    0.883  1.67
  Kirkman (EB)          0.754    0.337     2.24    0.026  1.67
  Municipal (EB)       -1.438    0.335    -4.29    0.000  1.68


Regression Equation in Uncoded Units

Square Root Passenger Delay = 3.474 - 3.189 LOCATION (L)_Del Verde (EB)
                              - 2.216 LOCATION (L)_Fun Spot (EB)
+ 0.050 LOCATION (L)_Grand
                              National (EB) + 0.754 LOCATION (L)_Kirkman (EB)
                              - 1.438 LOCATION (L)_Municipal (EB)
                              + 0.0 LOCATION (L)_Universal (EB)


Fits and Diagnostics for Unusual Observations

     Square Root
       Passenger
Obs        Delay    Fit   Resid  Std Resid
 56        0.000  4.228  -4.228      -2.48  R
```

67	8.124	4.228	3.896	2.29	R
77	9.695	4.228	5.468	3.21	R
80	0.000	4.228	-4.228	-2.48	R
87	0.000	4.228	-4.228	-2.48	R
108	0.000	3.523	-3.523	-2.07	R
110	0.000	3.523	-3.523	-2.07	R
112	0.000	3.523	-3.523	-2.07	R
117	0.000	3.523	-3.523	-2.07	R
118	0.000	3.523	-3.523	-2.07	R
119	0.000	3.523	-3.523	-2.07	R
121	0.000	3.523	-3.523	-2.07	R
122	0.000	3.523	-3.523	-2.07	R
123	7.937	3.523	4.414	2.59	R
129	0.000	3.523	-3.523	-2.07	R
153	0.000	3.523	-3.523	-2.07	R
180	7.141	2.036	5.105	3.00	R
184	9.560	2.036	7.524	4.42	R
186	6.473	2.036	4.437	2.61	R
225	4.472	0.285	4.187	2.46	R
244	3.873	0.285	3.588	2.11	R
265	4.796	1.257	3.539	2.08	R
271	5.292	1.257	4.034	2.37	R
277	4.796	1.257	3.539	2.08	R
282	5.196	1.257	3.939	2.32	R
300	5.385	1.257	4.128	2.43	R

R Large residual

Residual Plots for Square Root Passenger Delay



Passenger delay westbound

Results for: Worksheet 4

Regression Analysis: Square Root versus Condition (1, Condition (2, uni*cond1, ...

```
Method

Categorical predictor coding  (1, 0)

Continuous predictor standardization
Levels coded to -1 and +1

Predictor         Low  High
Condition (1)       0     1
Condition (2)       0     1
uni*cond1           0     1
uni*cond2           0     1
kirk*cond1          0     1
kirk*cond2          0     1
GrandN*cond1        0     1
gradN*cond2         0     1
Municipal*cond1     0     1
Municipal*cond2     0     1
Del verde*cond1     0     1
Delverde*cond2      0     1
uni*cond1_1         0     1
funspot*cond 1      0     1
funspot*cond2       0     1


Stepwise Selection of Terms

α to enter = 0.05, α to remove = 0.05


Analysis of Variance

Source           DF   Adj SS   Adj MS  F-Value  P-Value
Regression        5   531.13  106.226    37.52    0.000
  LOCATION (L)    5   531.13  106.226    37.52    0.000
Error           306   866.35    2.831
  Lack-of-Fit    26    42.57    1.637     0.56    0.963
  Pure Error    280   823.78    2.942
Total           311  1397.48


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.68262  38.01%     36.99%      35.55%


Coded Coefficients

Term                    Coef  SE Coef  T-Value  P-Value   VIF
Constant              -0.000    0.233    -0.00    1.000
```

```
LOCATION (L)
  Fun Spot (WB)          1.586    0.330     4.81    0.000  1.67
  Grand National (WB)    4.069    0.330    12.33    0.000  1.67
  Kirkman (WB)           2.771    0.330     8.40    0.000  1.67
  Municipal (WB)         2.250    0.330     6.82    0.000  1.67
  Universal (WB)         3.333    0.330    10.10    0.000  1.67


Regression Equation in Uncoded Units

Square Root Passenger Delay = -0.000 + 0.0 LOCATION (L)_Del Verde (WB)
                              + 1.586 LOCATION (L)_Fun Spot (WB)
+ 4.069 LOCATION (L)_Grand
                              National (WB) + 2.771 LOCATION (L)_Kirkman (WB)
                              + 2.250 LOCATION (L)_Municipal (WB)
                              + 3.333 LOCATION (L)_Universal (WB)


Fits and Diagnostics for Unusual Observations

     Square Root
       Passenger
Obs        Delay    Fit   Resid  Std Resid
118        7.483  4.069   3.414       2.05  R
126        0.000  4.069  -4.069      -2.44  R
129        0.000  4.069  -4.069      -2.44  R
130        9.116  4.069   5.047       3.03  R
131        9.524  4.069   5.455       3.27  R
132        0.000  4.069  -4.069      -2.44  R
133        0.000  4.069  -4.069      -2.44  R
138        8.246  4.069   4.177       2.51  R
147        0.000  4.069  -4.069      -2.44  R
149        0.000  4.069  -4.069      -2.44  R
153        0.000  4.069  -4.069      -2.44  R
155        7.483  4.069   3.414       2.05  R
156        7.874  4.069   3.805       2.28  R
165       12.570  2.250  10.320       6.19  R
203        5.831  2.250   3.581       2.15  R
289        6.473  1.586   4.887       2.93  R

R  Large residual
```

Residual Plots for Square Root Passenger Delay